USING MICROSIMULATION TO EVALUATE TRAFFIC INCIDENT RESPONSES FOR TRAFFIC OPERATIONS CENTER DECISION MAKING

by

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ABSTRACT

One of the major challenges for Traffic Operations Center (TOC) operators is to determine the nature of their response to traffic incidents. This applies to both operators' training and real traffic management. While incidents vary by location and degree of disruption, operators' responses vary by how quickly they are implemented and what degree of actions they take. Operators can react instantaneously and divert traffic from an entire highway, or simply wait and apply a mild variable message. Travelers' delay under incident conditions depends not only on incident severity, but also on the effectiveness of response to an incident. This is an analysis of a wide range of incidents and responses for the set of critical locations on a test Salt Lake Valley freeway network. It uses VISSIM microsimulation to determine optimal responses under various incident conditions. Incident severity is represented through Incident Location, Incident Duration and Lane Closure. Incident response is defined through the Response Time, and Variable Message Sign (VMS) Levels and VMS Display Time. As expected, the resulting degree of incident disruption is mitigated by the speed of response and the proportion of drivers who divert. However, for certain minor incidents, a VMS induced traffic diversion might increase travelers' delay instead of reducing it.

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ACRONYMS

TOC	Traffic Operations Center
VISSIM	Verkehr In Stadten SIMulation (Traffic in Towns Simulation)
VMS	Variable Message Signs
TIM	Traffic Incident Management
UDOT	Utah Department of Transportation
UTL	Utah Traffic Lab
ITS	Intelligent Transportation Systems
NTIMC	National Traffic Incident Management Coalition
FHWA	Federal Highway Administration
MUTCD	Manual on Uniform Traffic Control Devices
DTA	Dynamic Traffic Assignment
DSS	Decision Support System
RTMC	Regional Traffic Management Center
DTM	Dynamic Traffic Management
IDSS	Intelligent Decision Support System
GIS	Geographic Information System
SP	Stated Preference
RP	Revealed Preference
OD	Origin-Destination

ATIS	Advanced Traveler Information Systems
HCM	Highway Capacity Manual

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CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Traffic Incident Management (TIM) is one of the major responsibilities of traffic managers and operators. Dealing with traffic incidents is a critically important piece of every transportation network management program. It should be considered in all stages of developing and implementing a network management and operations program as a key to reducing congestion. TIM programs exist for more than 20 years. At the long range, the main purpose and basis of all incident management programs has always been the reduction of traffic congestion.

Utah Department of Transportation (UDOT) Traffic Operations Center (TOC) and Utah Traffic Lab (UTL) have been working together on several projects in order to improve regional traffic management. The focus of these projects was creating an advanced training program for traffic operators that are responsible for incident management. The newest tool developed for that purpose is Salt Lake City (SLC) Traffic Platform. This tool provides a simulation based virtual environment for TOC operators' training.

SLC Traffic Platform integrates VISUM macrosimulation and VISSIM microsimulation software, combining strategic planning with traffic management. Data exchange with VISUM provides travel forecasts, while VISSIM replicates traffic flow and any available Intelligent Transportation System (ITS) measures. Traffic Platform uses this data feed for traffic state calculations. This kind of system architecture allows traffic operators to respond to various traffic conditions, including incidents, by changing and implementing ITS devices.

Before using SLC Traffic Platform for both training and real incident management, traffic operators need an assessment of possible incident responses they could implement. This research represents an evaluation of TOC operators' responses to various incident conditions on SLC freeway network. Operators' responses are designed to adjust to SLC Traffic Platform environment, once they are evaluated. This will allow for the best responses to each incident type to be applied first for the purposes of operators' training, and then tested for real-time incident management.

1.2 Traffic Incident Management and Response

Traffic incidents have been identified as one of the major contributors to increased congestion. The National Traffic Incident Management Coalition (NTIMC) estimates that traffic incidents are the cause of about one-quarter of the congestion on the U.S. roadways, and that every minute a freeway lane is blocked due to an incident results in 4 minutes of travelers' delay time.

According to Federal Highway Administration (FHWA) TIM Handbook published in 2000 (1): "Traffic incident is any non-recurring event that causes a reduction of roadway capacity or an abnormal increase in demand. Such events include traffic crashes, disabled vehicles, spilled cargo, highway maintenance and reconstruction projects, and special non-emergency events." The Manual of Uniform Traffic Control Devices (MUTCD) (2) defines traffic incident as "an emergency road user occurrence, a natural disaster, or other unplanned event that affects or impedes the normal flow of traffic." For the purpose of this research, the definition of traffic incident that is going to be deployed is: "Traffic incident is any non-recurring event that causes a reduction of roadway capacity or an abnormal increase in demand." Traffic incident analysis in this research starts from UDOT classification of roadway incidents, based on the number of lanes closed due to a traffic incident:

LEVEL 1: Not blocking any lane

LEVEL 2: Blocking less than one half of through lanes

LEVEL 3: Blocking at least one half of through lanes

LEVEL 4: Blocking all lanes and shoulder, no passage possible or permitted

It has been shown that improved TIM reduces both overall incident duration as well as secondary crashes. TIM is the systematic, planned, and coordinated use of human, institutional, mechanical, and technical resources to reduce the duration and impact of traffic incidents, and improve the safety of motorists, crash victims, and traffic incident responders. Effectively using these resources can also increase the operating efficiency, safety, and mobility (3).

Incident management entails an identifiable series of activities, which may be carried out by personnel from a variety of response agencies and organizations. These activities are not necessarily performed sequentially. The most detailed process of incident management is represented in the Freeway Management and Operations Handbook (3). According to this handbook, incident management process includes the following phases:

1) Incident detection is the process by which an incident is brought to the attention of the agency responsible for maintaining traffic flow and safe traffic operations

2) Incident verification entails confirming that an incident has occurred, determining its exact location, and obtaining relevant details about the incident
3) Motorist information involves activating various means of disseminating incident-related information to affected motorists
4) Incident response includes dispatching the appropriate personnel and equipment, and activating the appropriate communication links and motorist information media as soon as there is reasonable certainty that an incident is present
5) Site management is the process of effectively coordinating and managing on-scene resources
6) Traffic management involves the application of traffic control measures in areas affected by an incident
7) Incident clearance is the process of removing wreckage, debris, or any other element that disrupts the normal flow of traffic
8) Incident recovery consists of restoring traffic flow at the site of the traffic incident.

This research is focused on incident response as a part of the TIM process. Incident response here is defined from the TOC operators' standpoint. Incident response in this research will include the actions that traffic operators need to perform after they verify that the incident has occurred with their surveillance cameras. Effective response requires preparedness by each responding agency, for a variety of incident types. The adequate level of preparedness is achieved through training and planning, both as individual, and collectively with other response agencies. Figure 1 shows the timeline of stages in TIM process.

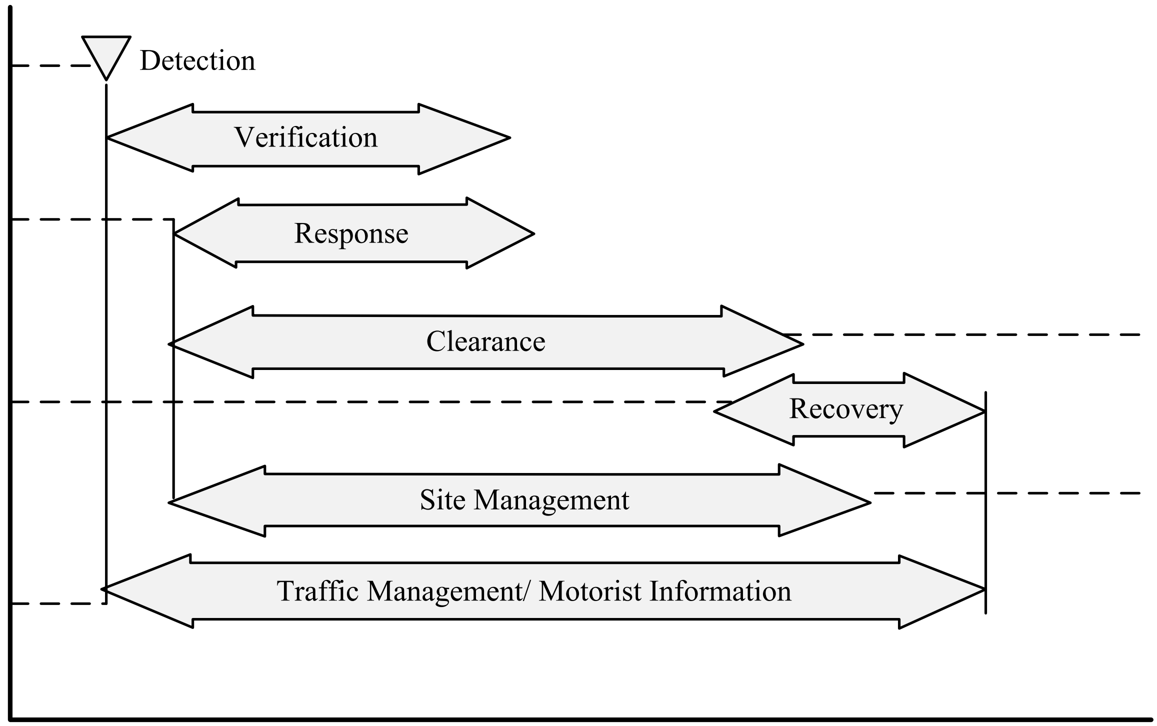


FIGURE 1 Timeline of Stages in the Traffic Incident Management Process – Reprinted with Permission (3)

1.3 Research Goal and Objectives

Effective use of TOC resources in incident situations improves operating efficiency and safety of the entire network. This results from reducing the time to detect and verify a traffic incident occurrence, implementing the appropriate response, safely clearing the incident, and managing the affected flow until full capacity is restored.

The research method introduced here links incident severity and operators' response. Incident severity is defined through Incident Location, Incident Duration and percentage of closed lanes. The operators' response level is defined in terms of their Response Time and percentage of traffic diverted due to VMS message content and display time.

The main goal of this research is to develop a set of incident response strategies that would optimize TOC operators' decision making in terms of time and response level, and minimize users' cost due to incident induced delay on the freeway network. In order to achieve that, the following objectives have been established:

- Identify test network for incident/response modeling and a set of "critical" locations on that network challenging for TIM operations
- Create incident/response scenarios for calibrated traffic models in VISSIM
- Analyze VISSIM outputs to establish the relationship between Incident Location and optimal incident response
- Provide a more detailed delay analysis for single critical location for different combinations of Incident Duration, Level of Closure, VMS Level and Response Time and determine the responses that give optimal results
- Conduct an analysis that shows if VMS Display Time is a relevant factor in TOC incident response process
- Provide recommendations for TOC incident response strategies based on the analysis of the obtained results.

This type of incident response analysis should show the impact of the operators' inadequate response. VISSIM micro-simulation outputs measure the consequences of operators' over/under response in terms of travelers' delay on the network wide level.

The research is organized in six chapters. The next chapter is a literature review on topics relevant for TOC incident response optimization. It is followed by the explanation of experiment design, data calibration and validation in the Methodology. The modeling outputs are presented in the Results chapter. The obtained results are analyzed in the Discussion that yields recommendations for the application of the conducted analysis. The final chapter contains the main conclusions of the research.

CHAPTER 2

LITERATURE REVIEW

The papers reviewed in this chapter summarize the previous research on topics relevant for traffic incident response. The first section discusses traffic incident modeling in general. The following two sections are about the previous research focused on incident response and decision making support systems. Since this research is about using VMS for traffic operators' response, part of the Literature Review is about the effectiveness of VMS in terms of drivers' response. The last group of reviewed papers is about potential negative impacts of traffic diversion. Finally, this chapter explains the remaining issues in the existing literature that this research addresses.

2.1 Incident Modeling

Traffic incident modeling approaches in the existing literature often rely on queuing models to predict travelers' delay. Fu and Rilett (4) modeled incident duration as a random variable within a deterministic queuing model approach. The model assumes constant arrival rate, and when there is no incident, a constant departure rate. The authors concluded that travelers' delay in incident conditions depends on several factors: incident severity/capacity reduction, incident duration, arrival pattern, traffic volume, and the future time of vehicle's arrival at the incident location.

Fu and Hellinga (5) developed a fuzzy queuing model that can be used to predict the possible delay or interval of delay that a vehicle will experience at an incident location. The delay prediction is based on real-time information on current queuing condition, future traffic arrival, lane closing and the vehicle's arrival time. The model allows continuous updates of estimates as new information is made available in real time. The delays as an output from the model are fuzzy numbers that can be mapped to linguistic terms for use in systems such as VMS.

Some authors have combined queuing models and simulation to assess the impacts of traffic incidents. Gursoy et al. (6) developed an estimation method for delays caused by traffic incidents. They used a queuing based approach and compared its results with a simulation model. The results from the queuing model are very close to the simulation results. The authors recommend the developed queuing model as an effective alternative for simulation for the purposes of incident management.

Another approach in incident modeling in the existing literature is Dynamic Traffic Assignment (DTA) based simulation. Ngassa (7) used DTA to analyze the impact of incidents on delay. DTA models produce spatio-temporal trajectories of all vehicles from their origin to their destination under a simulated environment. The proposed empirical delay estimation calculates incident induced delay by taking the difference of average travel times under normal conditions and incident conditions. Boyles (8) developed a simulation based delay prediction model that provides predictions in the context of uncertain incident duration, eliminating a significant source of error. The model accounts for uncertainty in predicting the incident duration. Failing to properly account for this will result in underestimating incident induced delays by 20%-50%.

2.2 Incident Response

Incident response as one of the stages of TIM has been examined from both travelers' and TOC standpoint. Subramaniam (9) developed a model for solving various network optimization problems. One of the problems deals with the resource allocation strategy for emergency and risk management. The goal was to reduce TOC Response Time defined as a sum of dispatch and travel time for emergency response vehicles.

Zografos et al. (10) developed an integrated decision-making framework for reducing freeway-incident delay through the minimization of the duration of the incident. The focus of the study was on the mathematical model that will improve freeway incident management and the deployment of incident response strategies. Incident delay depends heavily on the total incident-remedy time, so the reduction of the dispatch and travel time of the traffic flow restoration units is expected to result in substantial savings of incident delay. Zografos (11) did another study on incident response logistics and the effective deployment of incident response resources. The objective was to develop a support system that will provide districting, dispatching, and routing of response units.

Pal and Sinha (12) also focused their traffic incident response research on the appropriate resource allocation. The goal was to determine the optimal hours of operation, fleet and crew sizes, dispatching policies, areas of operation, and routing patterns, in order to maximize the response system's efficiency.

Chahuan (13) analyzed the possibilities of traffic surveillance to improve traffic incident response system and reduce incident induced costs for the travelers. He used a DTA system to improve wide-area incident response through information sharing and coordination.

Ozbay et al. (14) evaluated the benefits of various incident management strategies and technologies using and integrated simulation tool. This tool can generate incidents and test various response strategies and technologies. The authors used South Jersey as a test network, and the evaluated strategies included VMS, freeway service patrol, and cell phone users that detect and verify freeway incidents. The evaluated strategies showed positive impact on reducing incident durations while being cost effective.

Wirtz et al. (15) used a DTA model as a tool for preplanning strategies for managing major freeway incidents. It was found that the best response action to a given incident scenario was not necessarily intuitive. Implementing the wrong response could worsen congestion on the directly impacted freeway and its surrounding network. The simulation also showed that congestion increases with delayed response, underscoring the benefits of preplanning to speed the implementation of effective incident response actions. The study considers only ramp metering as a response to defined incident conditions and examines only one incident location, while not explaining the choice of that particular location. It is interesting that the study compares the effectiveness of incident response strategies on the freeway level and on the network wide level with alternate routes included. The test of the response time effectiveness showed that the longer response time increases congestion but not significantly. Authors expected a larger effect here, but did not consider that longer response time might be beneficial in some cases.

2.3 Decision Support Systems

Decision Support Systems (DSS) are developed as new TOC incident response tools to predict the diversion impacts based on selection of different parameters. These highly efficient methods take into account traffic volumes, incident severity, vehicle speeds, and geometric features of the road. Every DSS is based on the process of predicting the impacts of alternative sets of options.

The first versions of DSS did not provide needed prediction of traffic conditions fast enough for the TOC operators' timely response. Bhavsar et al. (16) developed a DSS to calculate the delay as a result of a particular diversion strategy. The input data were geometric and traffic variables, and the tool uses support vector regression to predict the benefits of diverting traffic. The study found 15% difference between the predictions of the model and the simulation, demonstrating the feasibility of DSS.

Fries et al. (17) examined the effectiveness of timeliness of using a detailed microsimulation to support personnel in a regional traffic management center in real-time decision making. The authors used a Paramics microsimulation tool to examine whether it could provide decision information as quickly as desired by regional traffic management centers. Only certain combinations of incident durations and simulation accuracy satisfied the decision-time constraints for real-time decision support. The conclusion was that increasing the computational resources or reducing the size of the traffic network can provide DSS for longer incidents at higher accuracies. Microscopic simulation will further be improved to finally become a tool that traffic managers and operators can use in real-time decision making.

Hoogendoorn et al. (18) developed a two-step scenario-based approach to support the traffic operators in Regional Traffic Management Centers (RTMC). A fully automated calibration approach for the input and parameters of a macroscopic simulation model is described as the major contribution of this research. The paper focuses on Dynamic Traffic Management (DTM) as an integrated and coordinated deployment of measures, anticipating the future changes in traffic conditions. The DSS developed here is called BOSS and provides the operators with conditional predictions on the future state of traffic network given the current state.

Hasan (19) proposed a comprehensive framework for an Intelligent Decision Support System (IDSS) for traffic congestion management. The study uses transportation network equilibrium modeling in Geographic Information System (GIS) - based environment. The developed system reduces the dependability on the expertise and level of education of the transportation planners, transportation engineers, or any transportation decision makers.

2.4 VMS Impact on Traffic Diversion

Drivers' response to VMS is one of the inputs for modeling impacts of VMS induced diversion under incident conditions. Papers reviewed in this section are important for assumptions related to diversion rates made in this research. Previous research shows that different VMS messages result in different diversion rates. Using specific VMS message content significantly affects drivers' diversion behavior.

The ideal way to study drivers' diversion behavior under the influence of VMS is through direct observation of actual decisions in real-world systems. However, this is not practical due to limited use of VMS. Since this research is oriented towards drivers' behavior in traffic incident conditions, it would be even harder to provide enough data to study the impact of VMS. Several data collection methods are used to examine drivers' response to VMS in previous research.

The impact of VMS on traffic diversion was often evaluated using Stated Preference (SP) and Revealed Preference (RP) surveys. The advantage of SP surveys is that it provides insight into possible respondents' reactions in scenarios that are difficult to test in reality. The advantage of RP is that it reports actual, experienced behavior. The disadvantage of SP is that respondents often base their stated preference on their revealed preference, in order to justify their real-life behavior. This type of “justification bias” is often eliminated by combining both SP and RP in research. The drawbacks of surveys are also their costs.

Polydoropuolou et al. (20) analyzed data on travelers’ route-switching decisions from California Bay Area commuters. They used stated preference (SP) and revealed preference (RP) surveys to explore response to traveler information. The results indicated that travelers’ decision changes are determined by expected delays on the original route, travel time on alternate routes, and information sources. The conclusion was that travelers are more likely to respond to specific quantitative delay information. This conclusion is important because it supports the assumption that diversion increases if expected delay is displayed in addition to incident occurrence information.

Khattak et al. (21) conducted mail surveys in San Francisco and Chicago areas and asked respondents about the effects of en-route traveler information and their diversion decisions. The number of drivers who diverted in response to traveler information was greater in Chicago. This shows that location characteristics influence diverting behavior.

Peeta and Ramos (22) conducted research on the relationship between VMS message content and drivers’ behavior. If the message content is significant factor in drivers’ response, traffic operators can use it as a control variable to influence network traffic conditions. The authors used an SP survey and developed logit models for drivers’ diversion decisions. VMS messages were classified into two categories: passive and active. A passive message provides descriptive information of the problem the driver may encounter. An active message provides explicit route guidance. When the expected delay on the current route is at least 10 minutes, 53% of respondents indicated they would divert. The results showed that drivers' propensity to divert increases as information content increases, provided the information content is considered valuable. Expected delay and best alternate route are considered valuable information in terms of influencing diversion decisions. The analysis suggests that content in terms of the level of detail of relevant information significantly affects drivers' willingness to divert. Another study conducted by Peeta et al. (23) also shows strong correlation between VMS message content and drivers' response.

Martin et al. (24) conducted the evaluation of UDOT VMS technologies in 2005. They found that about 50% of surveyed drivers would respond to VMS warnings related to traffic incidents and safety. About 80% of surveyed drivers would respond to a VMS message that includes travel time or delay prediction. These findings will be used to support assumptions related to VMS induced diversion rates in this research.

Another way to examine VMS impacts on drivers' diversion behavior is by using the driving simulator. These types of experiments have been proposed and tested as an effective and practical approach to assess drivers' diversion decisions. The advantage of simulators is that they are developed enough to consider day-to-day evolutions of individual decisions, the interaction among drivers, and the dynamic nature of traffic conditions.

Liu and Mahmassani (25) addressed en route path switching behavior under real-time traveler information. The analysis focused on the day-to-day dynamics of drivers' departure time and route decision process in response to real-time traffic information. A dynamic interactive traveler simulator was used to obtain the data. Drivers' diversion behavior, both pre-trip and en-route, is influenced by the reliability of real-time information. Drivers tend to switch route in response to higher differences between the predicted arrival time and their own preferred arrival time. This again shows the importance of quantitative delay information in VMS messages.

Many studies on VMS impact used loop detector data on traffic volumes to calculate the percentage of diverted traffic. This could be a very reliable source of data, if observations lasted over a long period of time.

Schiesel and Demetsky (26) evaluated the effect of VMS on drivers' behavior in the Hampton Roads area of Virginia. They collected traffic volume data from the loop detectors under various VMS messages. The difference between the number of vehicles diverting while VMS was on and off was referred to as diversion percentage. The average diversion percentage was very low. Reasons for this include the "weak" message displayed on the system, the unwillingness of drivers to divert, and the distance from the secondary route. Studies using loop detector data to estimate diversion rates attributable to VMS have found that diversion is minimal when vague messages are displayed or a distant alternate route is the only option.

Foo and Abdulahi (27) evaluated the impact of VMS messages on traffic diversion using 3 years of loop detector data in Toronto, Canada. They have found that the average VMS message change can alter the diversion rate by up to 5%, and can shift volume up to 300 vph. The number of diverted drivers depends strongly on the specific initial and final messages, and VMS location.

Huo and Levinson (28) showed that given a comparable alternate route and specific information on the VMS, particularly regarding incidents, diversion can be significant. The purpose of their study was to provide guidance on investing in VMS. They performed a statistical analysis to test the variation of diversion rate with and without VMS. They also used a discrete choice model to predict drivers' response to VMS. Measures of effectiveness were travel time savings, total delay reduction, and safety improvements. The results of statistical analysis showed that VMS can increase drivers' diversion rate significantly by providing warning messages about the traffic conditions on the road. VMS did not show significant effect on travel time reduction and safety improvements. However, together with ramp-meters, VMS significantly reduced total delay during an incident in both peak and off-peak periods.

Schroeder and Demetsky (29) estimated drivers' reactions to VMS to improve the effectiveness of traveler information. They collected loop detector data and investigated the impacts of existing message strategies. The goal was to determine messages that maximize diversion for specific circumstances and develop new messages for the future deployment. They analyzed various message types and two incident scenarios: one encouraging alternate route, the other encouraging exiting from the freeway. The results showed trends where the use of particular words in messages is more effective than the use of others in achieving diversion. The study recommends that travel time estimates for both original and alternate routes be provided on VMS. Specific wording should be used to induce congestion or simply provide information about the events on the road ahead. The authors concluded that usage of appropriate VMS messages results in reductions of delay, fuel consumption, emissions, and secondary traffic incidents.

The findings from the literature review of VMS impacts on traffic diversion are summarized in Tables 1 and 2. The studies that examined the effectiveness of VMS are given in Table 1, while Table 2 presents the studies that estimated diversion rates related to VMS content. The content of the VMS message, the location of the VMS and drivers' characteristics all contribute to the diversion rates. The review of previous research will be used as a support for modeling VMS induced traffic diversion.

Table 1 VMS Effectiveness - Summary of Reviewed Studies (20-29)

Ref	**Authors**	**Year**	**Variables Estimated**	**Results and Conclusions**
Survey Data Collection				
20	Polydoropuo lou et al.	1996	Drivers' willingness to divert	Displaying quantitative delay information increases diversion
21	Khattak et al.	1998	Drivers' willingness to divert	Locations characteristics influence diversion behavior
22	Peeta and Ramos	2000	Diversion rates	Diversion rates increase if expected delay and alt. route is displayed on VMS
23	Peeta et al.	2001	Diversion rates	Strong correlation between VMS message content and diversion rates
24	Martin et al.	2005	Drivers' willingness to divert	About 80% of drivers would respond to travel time or delay displayed on VMS
Driving Simulator Data Collection				
25	Liu and Mahmassani	1998	Drivers' willingness to divert	Diversion rates increase as expected delay increases
Loop Detectors Data Collection				
26	Schiesel and Demetsky	2000	Diversion rates	Diversion rates are low when "weak" messages are displayed on VMS
27	Foo and Abdulahi	2006	Diversion rates	The number of diverted drivers depends on VMS message content
28	Huo and Levinson	2006	Travel Time, Delay, Safety	Adequately deployed VMS results with significant delay reductions
29	Schroeder and Demetsky	2011	Drivers' willingness to divert	Travel times for original and alternate routes should be displayed on the VMS

Table 2 Diversion Rates for Different VMS Message Contents (37)

Location and Time	**Study Approach**	**Drivers' Characteristics**	**Message Content**	**Diversion Rate**
UK 1995	Measurements	Relevant drivers	Accident; Advised route	40%
UK 1998		Relevant drivers	Long delay; Incident location	53%
France 1998	RP Survey	Relevant drivers	Advised route	40%
Italy 1998	RP Survey		Advised route	43%
Nine European Cities 1994-1998	RP Survey		Long delay; Incident location	13%
UK 1999	RP Survey	Work trip	Comparative travel time	2%
UK 1999	RP Survey	Non-work trip	Comparative travel time	15%
Australia 2007	SP Survey		Predictive delay	56%
Australia 2007	SP Survey		Best route	64%
Indiana, 2005	SP Survey	Familiar drivers	Incident occurrence	27%
Indiana, 2005	SP Survey	Familiar drivers	Incident location	29%
Indiana, 2005	SP Survey	Familiar drivers	Expected delay	49%
Indiana, 2005	SP Survey	Familiar drivers	Best alternate route	48%
Indiana, 2005	SP Survey	Familiar drivers	Incident location; Best alternate route	69%
Indiana, 2005	SP Survey	Familiar drivers	Incident location; Expected delay	80%
Indiana, 2005	SP Survey	Familiar drivers	Expected delay; Best alternate route	82%
Indiana, 2005	SP Survey	Familiar drivers	Incident location; Expected delay; Best alternate route	93%

2.5 Impact of Traffic Diversion on Traffic Operations

The purpose of VMS-induced traffic diversion under incident conditions is to result in shorter travel times and delay reductions. Studies reviewed here mostly evaluate traffic diversion as one of incident management strategies. A few studies also deal with the optimization of diversion rates.

Cragg and Demetsky (30) conducted one of the first studies that imply the potential negative impact of diversion strategies on alternate routes. They emphasized the need to analyze operational characteristics of both the freeway and alternate routes before implementing the diversion. The methodology for analyzing diversion strategies uses CORSIM. The simulation models were tested and applied to several case studies. The purpose was to determine critical freeway volume at which diversion becomes advantageous. The results showed that for incidents where only one lane is closed, there is often an optimum diversion percentage beyond which freeway delays increase.

Lin and Kou (31) emphasized both positive and negative impacts of traffic diversion. Their main research question was whether using alternate route can actually save driver's travel time. They conducted traffic simulations to compare travel times on original and alternate routes. The simulation results from the case study provided multiple benefits for drivers using the alternate route. The results verified the value of alternate route operations in response to a major freeway incident.

The study conducted by Huaguo (32) uses computer simulation approach to evaluate route diversion strategies in Sarasota County, Florida. The advantage of this study is that it models both the freeway and arterials simultaneously. Three scenarios are simulated: no incident, incident without management strategies, and incident with management strategies. Adequate diversion rate, incident duration of 1 hour and two freeway lanes blocked defined each of the three scenarios. The findings from the CORSIM analysis indicate that the route diversion strategies may reduce overall network delay by an average 21%. The results imply that the percentage of diverted traffic volume has a great impact on the total delay of the entire network. The authors found that a 10% diverted traffic volume gives minimal total network delay based on the case study.

Dia et al. (33) quantified the effects of different incident management strategies. The evaluation was based on a large-scale micro-simulation model covering part of Gold Coast, Australia. The authors combined VMS information and signal timing adjustment to determine the optimal diversion rate. The obtained optimal diversion was 30%. It reduced delay by 9%, number of stops by 22% and travel times by 3%. This research is significant because it considers the parameters that could be used for diversion optimization.

Liu and Chang (34) developed a diversion control model that optimizes detour rates and arterial signal timings. The model produces three types of control parameters: critical ramps for diversion, dynamic diversion rates, arterial signal timing. The goal was to apply this model in incident management. The results showed that the optimization of diversion rates substantially improves the utilization of capacity.

Yin et al. (35) conducted a research that associates diversion occurrence with incident characteristics. The authors emphasize that the significance of studying diversion behavior relates to its potential negative impact. Diversion alleviates some congestion on one route by reducing traffic on it. Yet, overall congestion may be merely transferred to other routes. Congestion transfer is likely to occur when traffic is diverting from freeways to arterial routes. Another factor contributing to congestion transfer is that the traffic management plans for diversion routes are designed for normal traffic conditions. This paper further explains the incident characteristics that could trigger diversion behavior.

Cuneo et al. (36) based their evaluation of diversion strategies on several case studies. They used a microscopic traffic simulator to evaluate the traffic control design. The approach was to measure total network travel time and origin-destination (OD) specific travel times. The results showed that even when route diversion reduces the demand for the ramp, the bottleneck forms later and a larger mainline disturbance is generated. The optimal diversion rate also depends on current traffic demand. This indicates the necessity of performing a detailed evaluation to identify diversion strategy impacts before it is implemented in the field.

2.6 Remaining Issues in the Existing Research

Previous studies have compared incident impact when there is no VMS available to incident impact with VMS presence. This research examines the incident impacts under different levels of drivers' response to VMS. Rather than minimizing TOC Response Time, the research addresses the impact of TOC Response Time on travelers' delay.

The Literature defines the Response Time as a "dispatch time" for emergency vehicles. Here, we re-define Response Time as the time that TOC operators need to display the VMS message. Thus the Response Time determines the VMS message display time. While many studies deal with the impact of VMS message content, there is a lack of research results that show the impact of VMS message display time on traffic. When VMS impacts are examined, previous research shows the benefits of VMS deployment. However, there is a need to balance VMS induced diversion rates, since the impacts of traffic diversion could be negative for arterial traffic.

Modeling information dissemination via VMS was conducted using DTA models for the purpose of route choice prediction. The probability of diversion was based on travel time information displayed on VMS. These studies are mostly traveler behavior oriented and show that VMS as a part of incident response reduces travelers' delay. Advanced Traveler Information Systems (ATIS) are considered to have a positive impact on reducing the incident duration. This research also has the ultimate goal of reducing travelers' delay, but addresses VMS induced diversion from the perspective of TOC operators in order to develop a tool for an effective incident response.

CHAPTER 3

METHODOLOGY

The methodology proposed here is developed to test various combinations of traffic incidents and operators' responses on the Salt Lake Valley freeway network. This method should identify the operators' responses that result in minimum traveler delay under defined incident conditions. The field does not provide enough incidents to deliver detailed insight, and testing operators' response to traffic incidents requires experimental environment. Validated VISSIM microsimulation enables a suitable experimental design.

3.1 Test Network and Incident Locations

Test network for incident/response modeling is Salt Lake Valley freeway network. This network is in the basis of SLC Traffic Platform, which is developed for both training and real incident management in the UDOT TOC.

After defining the test network, the next step was to choose the locations on the test network that would serve for incident modeling. The choice of "critical" locations is based on the discussion with the UDOT TOC traffic operators. This discussion was needed because this research is not simply focused on the locations with the most frequent crash occurrence. Critical locations are the locations on the freeways that are difficult to manage under traffic incident conditions.

This process started with a review of available crash data on the test network. The set of critical locations includes ramps or freeway lanes chosen in agreement with UDOT traffic operators. Incidents on these critical locations, shown in Figure 2, would cause serious traffic disruptions. From the perspective of traffic operators, responding to incidents on the critical locations would be a challenge. There are several reasons for this. The first reason is higher traffic volumes on these parts of the test network. The second reason is the problem of rerouting traffic and the possible lack of alternate routes. Finally, the lack of VMS or wrongly placed VMS could also be a problem, in case the drivers cannot see the message in time to reroute. Chosen critical locations for modeling incidents on the test network are:

1) Ramp I-80 WB to I-15 SB
2) I-15 SB just after I-80 / SR 201 interchange
3) SR 201 WB between I-15 and I-215
4) I-80 WB before State Street off-ramp
5) I-15 SB between 3300 S and 4500 S
6) I-80 WB “under” I-215 interchange
7) I-215 NB at 3100 S
8) Ramp I-80 EB to I-15 SB
9) I-215 SB at Highland off-ramp

3.2 Microsimulation Models Calibration

VISSIM microsimulation provides the outputs needed to determine best responses to different incident conditions on the test network. Defined test network, as the basis of

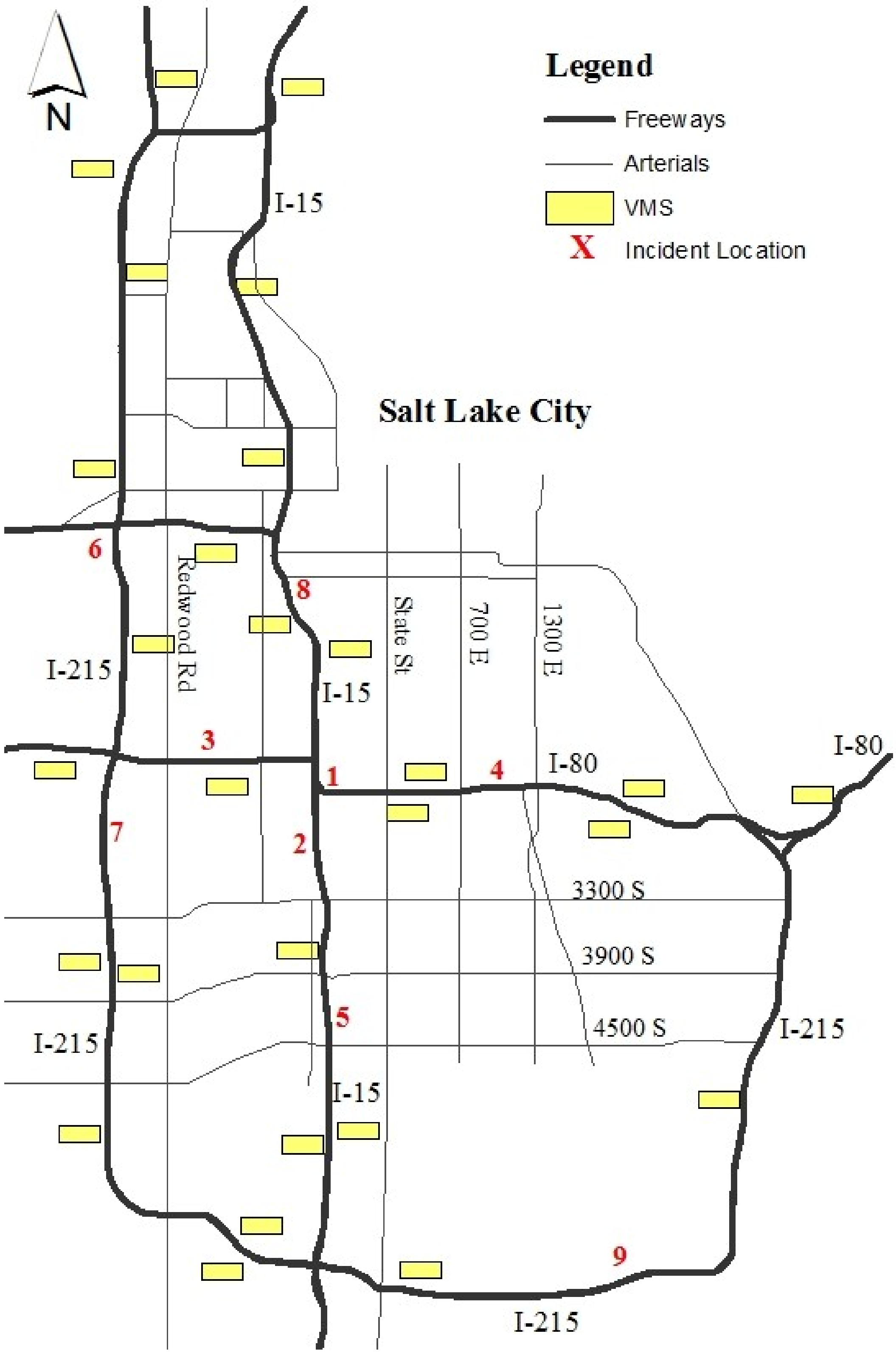


FIGURE 2 Test Network and Critical Incident Locations

SLC TrafficPlatform, was already available in the form of the VISUM Online model. VISUM models provide a good basis for VISSIM simulation.

Utilizing the data from the demand models to assist microsimulation model construction is the approach called “integrated modeling.” This approach is used because it is much more efficient than building the VISSIM models from scratch. VISUM On-line models were created, calibrated and validated based on data recorded from traffic monitoring station on freeway in Salt Lake Valley. The reference for the complete calibration process is the UTL report on VISUM Online (38).

The purpose of VISUM Online is to use available real-time and historic data to calculate current and forecasted traffic conditions on the network wide level. The accuracy of VISUM Online is based on how well the output from this system compares with the real data. The idea was to compare the traffic volumes from VISUM Online with the field measurements for the same links and for the same time period. Figure 3 shows a correlation between volumes from VISUM Online and the field volumes.

The coefficient of correlation (Figure 3) shows a strong correlation between the two data sets. However, only the correlation represented with an equation “y = x” would mean that VISUM Online traffic volume is completely accurate. VISUM Online still underestimates traffic volumes compared to field data, but produces comparable traffic measures.

For the purpose of this research, traffic models obtained from VISUM Online are appropriate. This way of VISUM-VISSIM integration will make this research applicable to SLC TrafficPlatform and it will be possible to implement the results of the research in TOC operators’ training and later on, in real-life traffic management.

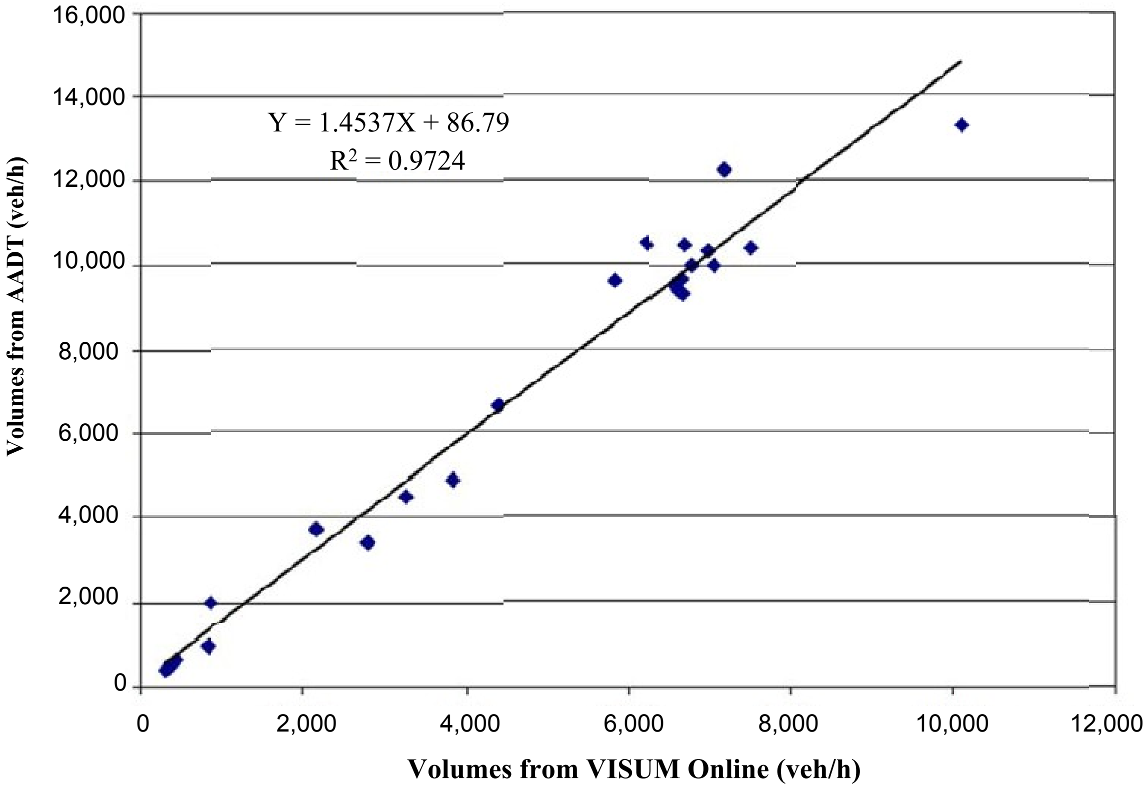


FIGURE 3 VISUM Models Calibration (38)

As a part of the TrafficPlatform, VISSIM microsimulation replicates traffic flow, incorporates different operators' decisions, and provides convenient outputs that can be used to compare performance measures of different operators' decisions. From the training perspective, this allows operators to gain experience. From real traffic management perspective, this allows implementation of tested decisions.

After importing freeway network with traffic volumes from the VISUM Online model, traffic is modeled for the PM peak between 4:00 PM and 6:00 PM. From the aspect of traffic operators, this period is the most critical for dealing with traffic incidents. This is when the incidents cause the greatest traffic disruption.

3.3 Model Inputs, Variables, and Outputs

This methodology is developed to simulate different incident conditions and potential TOC operators' responses to each incident. The simulation output should provide the performance measures for each response and thus determine the optimal decision for each set of incident conditions.

In VISSIM models each incident is defined by three variables: Incident Location, Incident Duration, and Lane Closure. In the modeling process, these parameters are variables, and with the change of these variables, incident conditions change too, requiring the appropriate response.

Incident Location could be any location from the defined set of critical locations on the test network. Incident Locations are varied only in the first set of performed simulations, in order to determine the overall relationship between the location of an incident and caused traffic disruption. This should also provide an insight into how much a location change can affect the required TOC response for the particular set of incident conditions.

Lane Closure, as the second variable that defines incident conditions, is the number of lanes closed for through traffic due to the incident. The impact of Lane Closure is analyzed in details in the second set of simulations, from only one lane closed to full freeway closure for the affected direction. The importance of this parameter is major since the actual capacity reduction is always greater than the percentage of lanes closed. The percentage of freeway section capacity available under incident conditions is defined in Highway Capacity Manual (HCM) 2010 (39). Table 3 represents the overall freeway

Table 3 Proportion of Segment Capacity Available Under Incident Conditions (HCM 2010, Exhibit 10-17)

Number of Lanes	Shoulder Dsiablement	Shoulder Accident	One Lane Blocked	Two Lanes Blocked	Three Lanes Blocked
2	0.95	0.81	0.35	0.00	N/A
3	0.99	0.83	0.49	0.17	0.00
4	0.99	0.85	0.58	0.25	0.13
5	0.99	0.87	0.65	0.40	0.20
6	0.99	0.89	0.71	0.50	0.26
7	0.99	0.91	0.75	0.57	0.36
8	0.99	0.93	0.78	0.63	0.41

capacity available based on the total number of lanes and number of lanes that are blocked due to the accident.

If a shoulder accident occurs and no lanes are blocked, up to 19% of the freeway capacity will still be lost, and 81% of the overall freeway capacity will be available. Also, in the case when one lane out of two per direction is blocked, Table 3 shows that only 35% of capacity will be available instead of 50% as a value that would be expected. The additional capacity reduction of 15% is a consequence of drivers rubbernecking as they pass the incident site. Some recent studies show that in addition to physical capacity reduction, the mere existence of the incident can further reduce the number of vehicles, i.e. capacity that can be served.

Incident Duration is the third variable that defines incident conditions in microsimulation models. In the literature, Incident Duration usually includes all phases of incident management, from incident detection and verification, emergency teams' response, to site clearance and traffic flow recovery. Some of the incident-modeling approaches are developed particularly to estimate Incident Duration.

The factors that could influence Incident Duration are incident type, traffic volumes, and responding teams' efficiency. It is challenging to give a precise prediction on Incident Duration. It is not unusual, however, for experienced response team or highway police patrol to give an estimation of the Incident Duration after they reach the incident site, determine incident severity and estimate how long the clearance might take.

In this research, Incident Duration is the period from the moment when the affected lanes are closed for traffic to the moment when the affected lanes are open again. In reality this would be treated as the "clearance time" or the time that emergency response teams need to clear the lanes for traffic. Three Incident Duration values are considered: 30 minutes, 60 minutes and 90 minutes. These values are chosen within the limits of simulation time from 4:00 PM to 6:00 PM for the PM peak hour. Incidents that require 90 minutes clearance are rare. However, these Incident Duration values should show the clear difference between the impact of shorter and longer traffic incidents.

Defining the incident in the VISSIM simulation can be done through time-dependent speed reduction areas and signal heads. Incident Location determines the position of traffic signal used to model the incident. Lane Closure determines the number of signal heads, with one signal head per each lane closed at the Incident Location. Incident Duration defines the "red" time of the signal used for incident modeling. Speed reduction areas are defined before and after the traffic signal to make sure the vehicles comply with incident conditions and slow down in the area of lane closure.

TOC operators' response to incidents is defined with three parameters: VMS Level, Response Time and VMS Display Time. These parameters show the effect of traffic diversion on network wide delay, VMS Level in terms of diversion intensity, and Response Time and VMS Display Time in terms of diversion duration.

The VMS Levels are four levels of drivers' response to the intensity of VMS message. Each VMS Level is related to a different VMS message content and results in different percentage of diverted traffic. Table 4 shows how VMS Levels are defined, with adequate illustrations of VMS message content and corresponding diversion rates.

Diversion rates correspondent to different VMS Levels are based on survey studies conducted in Utah, other states and several European countries. Rates of traffic diversion defined in this manner will ultimately be implemented in SLC TrafficPlatform for the purpose of traffic operators' decision making. VMS Level shows the effectiveness of VMS in terms of drivers' response to displayed messages. It also shows the effect of traffic diversion rates, and as such can serve to determine the intensity of diversion that would be appropriate for defined incident conditions.

Table 4 VMS Levels with Corresponding Message Contents and Diversion Rates

<table>
<tr><th>VMS Level</th><th>Message Content</th><th colspan="2">Message Example</th><th>Diversion Rate</th></tr>
<tr><td>Level 0</td><td>No message</td><td colspan="2"></td><td>No diversion</td></tr>
<tr><td>Level 1</td><td>Incident location</td><td colspan="2">Crash
4500 South
Right Lanes Blocked</td><td>5% - 10%</td></tr>
<tr><td>Level 2</td><td>Incident location;
Alternate route</td><td colspan="2">Crash
4500 South
Use I-215 as Alt</td><td>10% - 30%</td></tr>
<tr><td>Level 3</td><td>Incident location;
Delay;
Alternate route</td><td>Phase 1:
Crash
4500 South
Use I-215 as Alt</td><td>Phase 2:
Crash
4500 South
30 min Delays</td><td>40% - 80%</td></tr>
</table>

While no well-accepted standards exist yet for quantifying the drivers' responses to different VMS displays, we must come up with reasonable estimates of the route diversion compliance ratios under different VMS messages. For each VMS Level, the percentage of diverted drivers was randomly selected from the adequate range of values and distributed among the available alternate routes.

Using route choice in VISSIM to model drivers' response to VMS was also considered and rejected. Route choice modeling would be relevant only to VMS messages that display travel time information. Previous research shows that even mild VMS messages could divert some percentage of drivers. Further, diversion behavior cannot be explained solely by external environmental factors because every driver is different. A highly accurate route choice model that predicts VMS induced diversion in this case would require an extensive research of drivers' characteristics.

Response Time, as the second variable used to describe TOC operators' response, is the time that traffic operators need to display the VMS message, counted from the moment the lanes are closed due to the incident. It is assumed that VMS messages are still on display 5 minutes after each incident. Response Time as a variable is created to demonstrate the impact of operators' responsiveness on travelers' delay. Response Time, just as VMS Level, shows the impact of traffic diversion. The difference is that the Response Time shows the impact of the duration of traffic diversion rather than the intensity of the diversion. Knowing the values of Incident Duration and Response Time, the time of VMS message display can be calculated. This is how VMS Display Time, as the third variable used to describe incident response, is defined. So, the proposed methodology will show not only the effectiveness of VMS message content, but also the effectiveness of VMS message display time.

The implementation of VMS impact in VISSIM simulation is done through the partial routes feature that enables interactive change of vehicle routing. This feature fits well the VMS impact modeling. When constructing the simulation model, possible routes from each relevant VMS are studied. Not all VMS will contribute to the specific incident. Only VMS that can cause drivers to divert from the original route that includes Incident Location are considered. On their original routes drivers take freeways, while alternate routes include both freeways and arterials. Traffic diversion rates for all Incident Locations, for original and alternate routes are in Appendix A.

Variables that define TOC operators' response are the results of operators' decision making process under incident conditions. The method proposed here will test different decisions in terms of variables that define the response for various combinations of variables that define traffic incident on the test network. This research method is developed to indicate the importance of operators' training and capability to apply adequate strategies when managing traffic incidents.

3.4 Data Analysis Plan

Before starting the simulation process, the number of simulation models with inputs, variables and outputs needs to be determined. Table 5 shows inputs, variables, and outputs for microsimulation models for each simulations set. VISSIM provided four types of outputs: aggregate freeway delay, vehicle throughput, travel time, and network performance.

Table 5 VISSIM Simulation Elements

Simulation Set	Inputs	Variables	Outputs
1	• Freeway Network • Traffic Volume • Incident Duration • Response Time • VMS Locations • Original Routes • Alternate Routes • Lane Closure	• Incident Location (1 – 9) • VMS Level (0, 1, 2, 3)	• Aggregate Freeway Delay • Vehicle Throughput • Network Performance
2	• Freeway Network • Traffic Volume • Incident Location • VMS Locations • Original Routes • Alternate Routes	• Incident Duration (30, 60, 90 min.) • Lane Closure (16.7% - 100%) • Response Time (5, 10, 15 min.) • VMS Level (0, 1, 2, 3)	• Aggregate Freeway Delay • Vehicle Throughput • Travel Time • Network Performance
3	• Freeway Network • Traffic Volume • Incident Location • VMS Locations • Original Routes • Alternate Routes • Incident Duration • Signal Timing	• Level of Closure (16.7%, 50%) • VMS Level (0, 1, 2, 3) • VMS Display Time (20, 25, 30 min.)	• Aggregate Freeway Delay • Vehicle Throughput • Travel Time • Network Performance

The number of performed simulations will ultimately depend on the combinations of incident and response variables that we decide to test. Tested combinations of variables need to provide the adequate outputs in order to achieve goal and objectives of the research. Main inputs for each model are freeway network, traffic volume, and VMS locations. Original and alternate routes are inputs that depend on Incident Location and VMS location on the test network. Three sets of simulations were performed:

1) First simulations set where incident conditions were defined for each Incident Location with fixed Lane Closure and 60 minutes Incident Duration. Response was defined by 5 minutes Response Time and four VMS Levels
2) Second simulations set where incident was defined for Incident Location 2; Incident Durations of 30, 60, 90 minutes; and Lane Closure from one out of six lanes to full closure (from 16.7% to 100%). Response was defined by Response Time of 5, 10, and 15 minutes; and four VMS Levels
3) Third simulations set where incident was defined for Incident Location 2; Incident Duration of 30 minutes; and Lane Closure of 16.7% and 50%. Response was defined by Response Time of 5, 10, and 15 minutes; and four VMS Levels. This simulations set included traffic signal timing on the arterial intersections

3.5 Assumptions and Limitations

The methodology described in this chapter includes several assumptions. In general the number of values tested for each of the variables is limited, due to the large number of simulations that would result if we considered included more values. However, tested values for each variable are determined to show the effect of each variable on models' outputs.

Incident Locations vary only in the first simulations set to show if the optimal responses to similar incident conditions change with the location. The second and third simulations sets are related only to Incident Location 2, but provide more insight into the effects of other variables. The third simulations set tests only incidents that last 30 minutes but it is conducted to show the impact of VMS Display Time as a rarely considered feature of VMS in the previous research. The last simulations set should also indicate if traffic signals timing on the arterials create additional travelers' delay on the network wide level.

The assumption is that incidents, regardless of duration, start 10 minutes after the simulation period starts and that traffic operators need at least 5 minutes to respond. If VMS message is displayed, the message is still displayed 5 minutes after the incident is cleared. VMS messaging complies with UDOT TOC protocols and practice in traffic incident management. Once the decision about VMS Level is made, all relevant VMS will display the same VMS Level. The option of different VMS displaying different messages at the same time, depending on the distance of VMS from the incident location, is not considered. This approach might contribute to the response optimization, but would make modeling more complex, introducing VMS distance from the incident as a new variable.

A general limitation in all three simulations sets is the absence of arterial traffic in the background when freeway traffic diverts from the original routes. The reason for this is the lack of data and difficulty of obtaining traffic count data for arterial routes. This means that only freeway traffic is considered. Another limitation is the assumption that the arterial intersections work under free flow conditions for the first and second simulations set. This means that the delay caused by traffic signals on each signalized intersection is only accounted for in the third simulations set. Finally, the way that traffic diversion rates based on the VMS message content are assumed could be another limitation. The reason for this is lack of up to date research on VMS in general.

CHAPTER 4

RESULTS

The results are divided into four groups according to defined and obtained microsimulation outputs: aggregate freeway delay, vehicle throughput, travel time, and network wide delay. Results for each of the four groups of output are derived from three simulation sets where incident/response scenarios are defined with the following variables: Incident Location, Incident Duration, Lane Closure, Response Time, VMS Level, and VMS Display Time. In each of the four groups, the order of the results is from the first to the third simulation set, as defined in the Methodology.

All results are not included in this chapter. The selection of the results is made so that the tables and figures presented here explain general and unexpected findings, and relationships between the variables.

4.1 Aggregate Freeway Delay

Aggregate freeway delay is the result of node evaluation in VISSIM. Delay values were measured for several nodes around each incident location, with focus on nodes right before the incident locations. For each simulation set aggregate delay is obtained from the average delay and number of vehicles within each 5 minutes of the simulation. Tables 6-9 and Figures 4-9 show aggregate freeway delay results.

Table 6 Aggregate Freeway Delay for All Critical Locations and Defined Incident Conditions with respect to VMS Level for Two Simulation Hours

Location	2-Hour Demand	Number of Lanes	Lane Closure (%)	Capacity Reduction (%)	2-hr Delay (hr)			
					VMS Level 0	VMS Level 1	VMS Level 2	VMS Level 3
1	3,500	2	50.0	65.0	6	6	5	4
1	3,500	2	100.0	100.0	785	748	680	471
2	16,300	6	50.0	74.0	1600	1666	1309	31
3	13,300	5	40.0	60.0	250	50	40	19
4	8,000	3	66.7	83.0	479	439	412	375
5	16,800	5	60.0	80.0	1522	1527	1520	1537
6	3,400	3	100.0	100.0	830	833	826	820
7	10,800	4	50.0	75.0	632	552	263	33
8	10,700	3	66.7	83.0	1236	1313	1245	1150
9	10,100	3	66.7	83.0	3091	2925	2708	2346

Table 7 Average Freeway Delay per Vehicle for All Critical Locations and Defined Incident Conditions with respect to VMS Level for Two Simulation Hours

Location	2-Hour Demand	Number of Lanes	Lane Closure (%)	Capacity Reduction (%)	Average Delay per Vehicle (min)			
					VMS Level 0	VMS Level 1	VMS Level 2	VMS Level 3
1	3,500	2	50.0	65.0	0.103	0.103	0.086	0.069
1	3,500	2	100.0	100.0	13.457	12.823	11.657	8.074
2	16,300	6	50.0	74.0	5.890	6.133	4.818	0.114
3	13,300	5	40.0	60.0	1.128	0.226	0.180	0.086
4	8,000	3	66.7	83.0	3.593	3.293	3.090	2.813
5	16,800	5	60.0	80.0	5.436	5.454	5.429	5.489
6	3,400	3	100.0	100.0	14.647	14.700	14.576	14.471
7	10,800	4	50.0	75.0	3.511	3.067	1.461	0.183
8	10,700	3	66.7	83.0	6.931	7.363	6.981	6.449
9	10,100	3	66.7	83.0	18.362	17.376	16.087	13.937

Table 8 Aggregate Freeway Delay in Hours for Location 2 as a Function of Incident Duration, Lane Closure, Response Time and VMS Level

Lane Closure (%)	Incident Duration								
	30 minutes			60 minutes			90 minutes		
	Delay (h)	VMS Level	Response Time (min)	Delay (h)	VMS Level	Response Time (min)	Delay (h)	VMS Level	Response Time (min)
16.7	6	3	5	9	3	10	4	3	10
33.3	13	3	15	66	3	5	3	3	5
50.0	7	3	5	31	3	5	4	3	5
66.7	129	3	5	308	3	5	380	3	5
83.3	190	3	5	688	3	5	1256	3	5
100.0	694	3	5	2585	3	5	4182	3	5

Table 9 Aggregate Freeway Delay in Hours as a Function of VMS Display Time for Location 2

Lane Closure (%)	VMS Level	VMS Display Time (min)		
		20	25	30
16.7	0	275	275	275
	1	145	151	144
	2	114	96	93
	3	46	172	166
50	0	528	528	528
	1	422	422	408
	2	325	287	256
	3	121	60	137

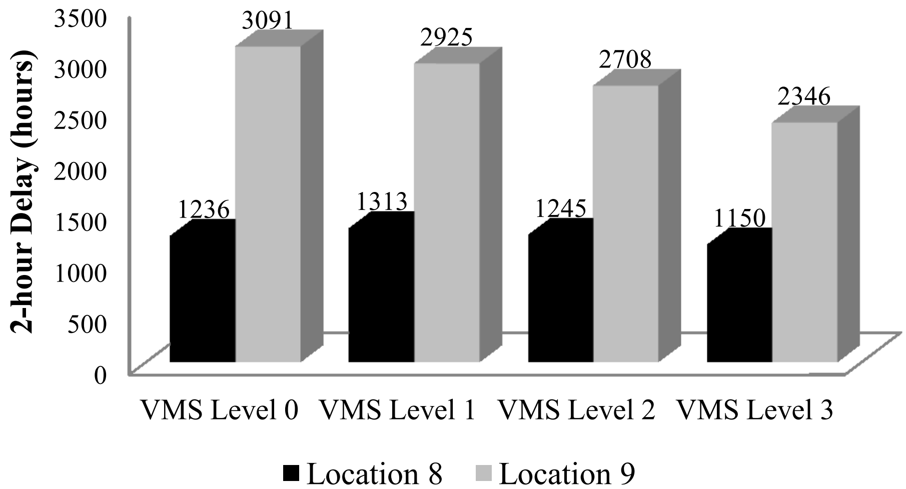


FIGURE 4 Aggregate Freeway Delay Comparison for Locations 8 and 9

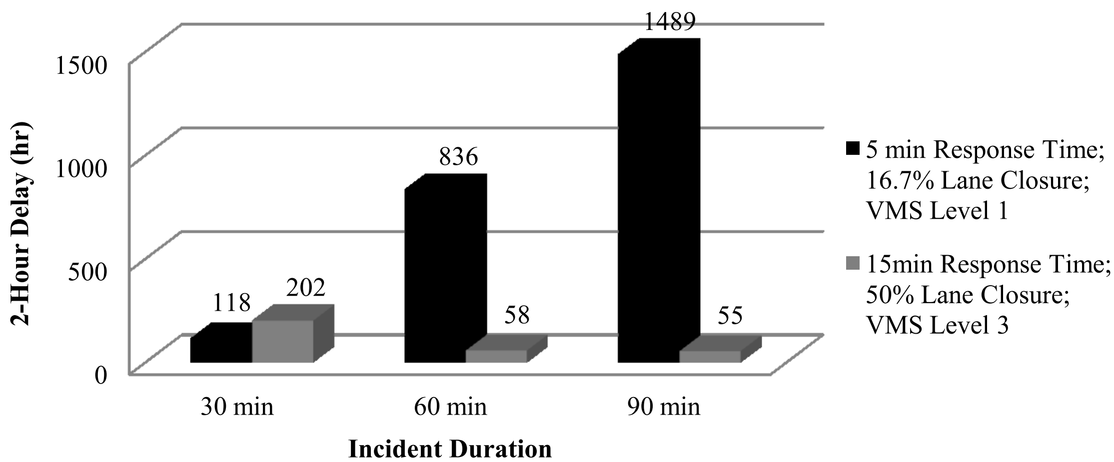


FIGURE 5 Aggregate Freeway Delay as a Function of Incident Duration for Two Different Scenarios at the Location 2

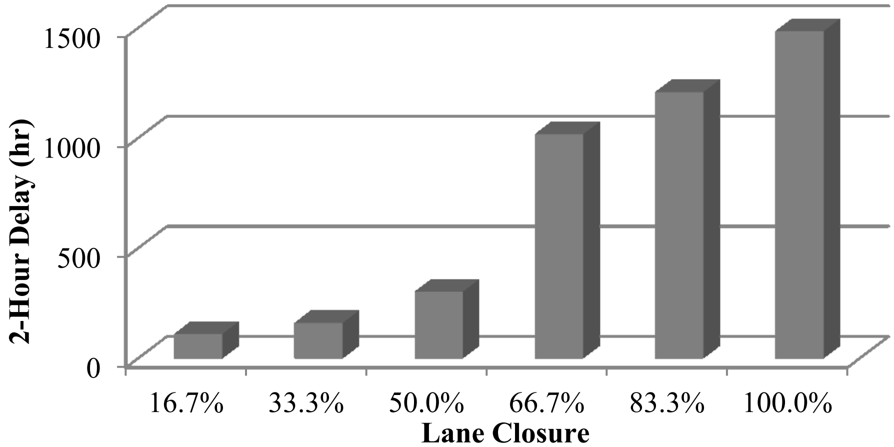


FIGURE 6 Aggregate Freeway Delay as a Function of Lane Closure for Location 2, 30 minutes Incident Duration, 10 minutes Response Time, and VMS Level 0

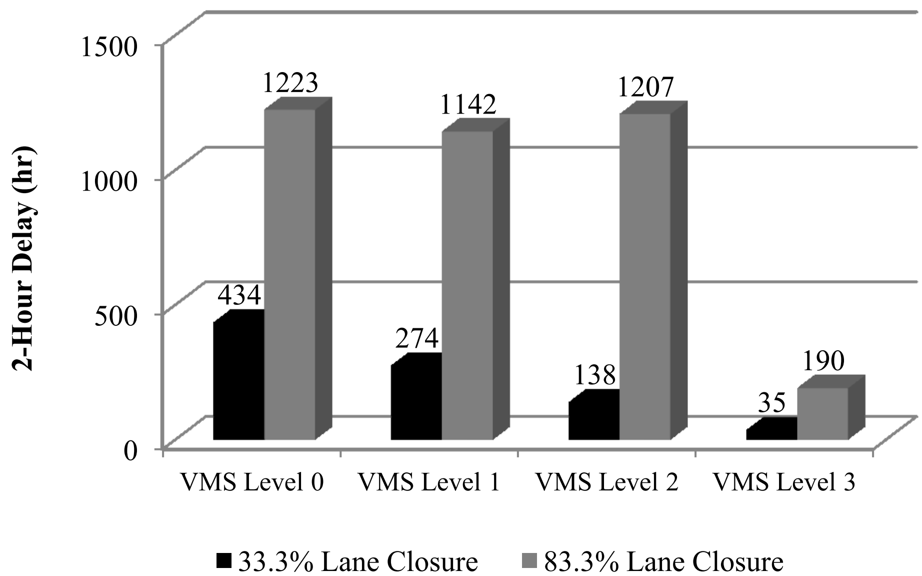


FIGURE 7 Aggregate Freeway Delay Comparison for Two Different Lane Closures and Various VMS Levels, for Location 2, 30 minutes Incident Duration, and 5 minutes Response Time

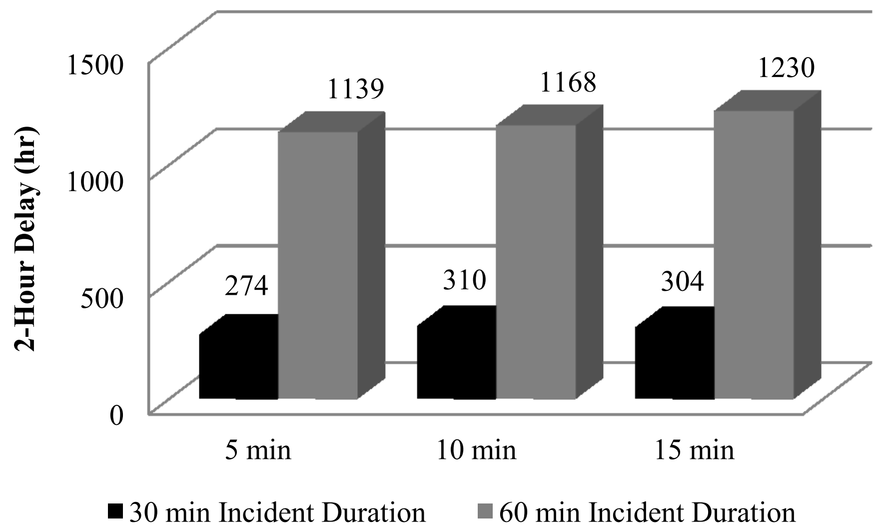


FIGURE 8 Aggregate Freeway Delay Comparison for Two Different Incident Durations and Various Response Times for Location 2, 33.3% Lane Closure, and VMS Level 1

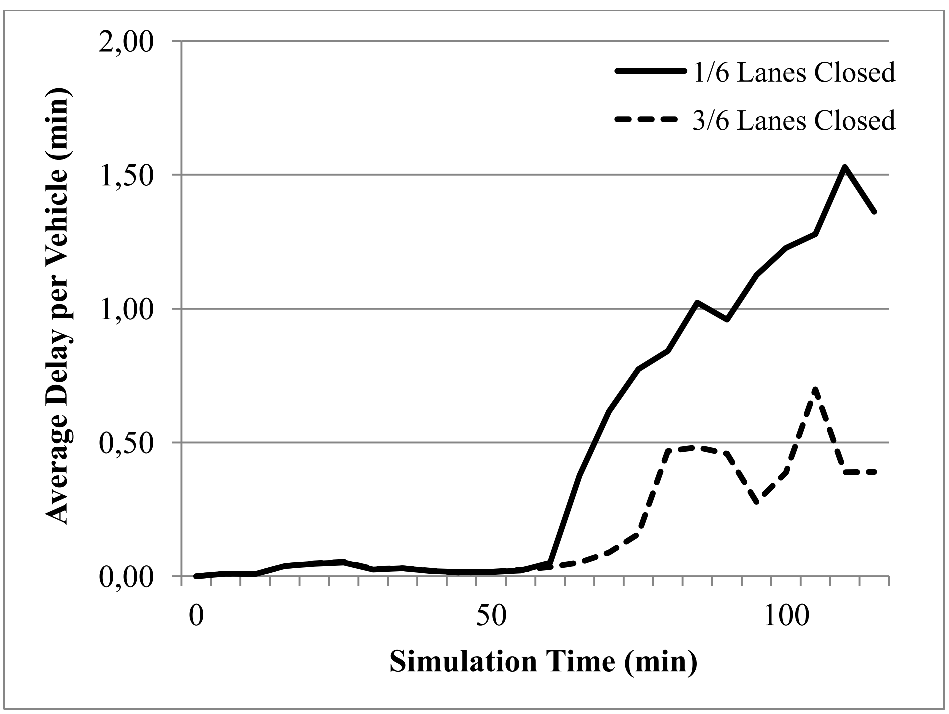
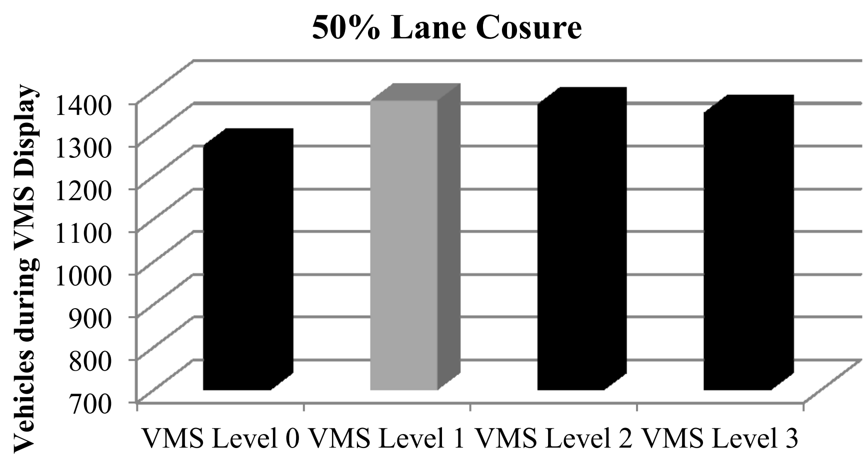


FIGURE 9 Average Delay per Vehicle as a Function of VMS Display Time for Location 2 and VMS Level 2

4.2 Vehicle Throughput

Vehicle throughput is the total number of vehicles bypassing the incident location and using both original and alternate routes. This output is obtained from the vehicle counts on measurement points on both original and alternate routes in VISSIM. Figures 10-15 and Tables 10-13 show vehicle throughput results. The results show the impact of all variables observed in three simulation sets.



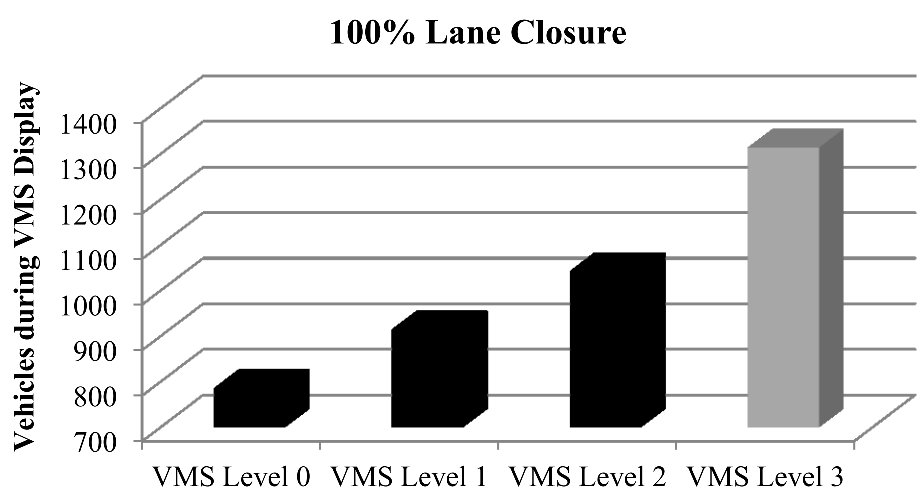
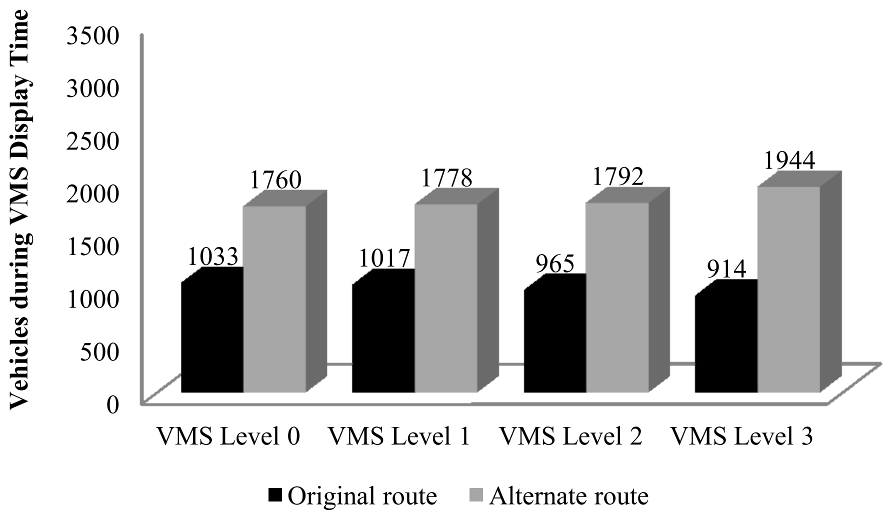


FIGURE 10 Vehicle Throughput Comparison for Two Different Lane Closures for Location 1



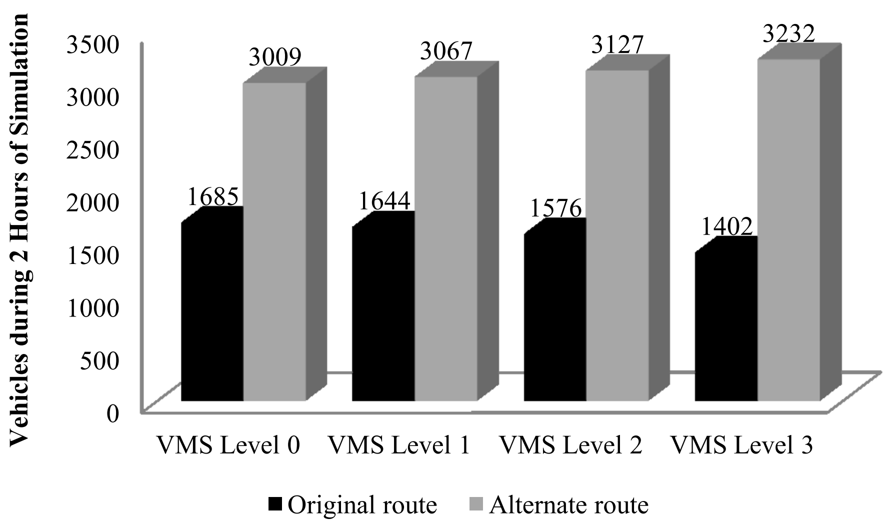
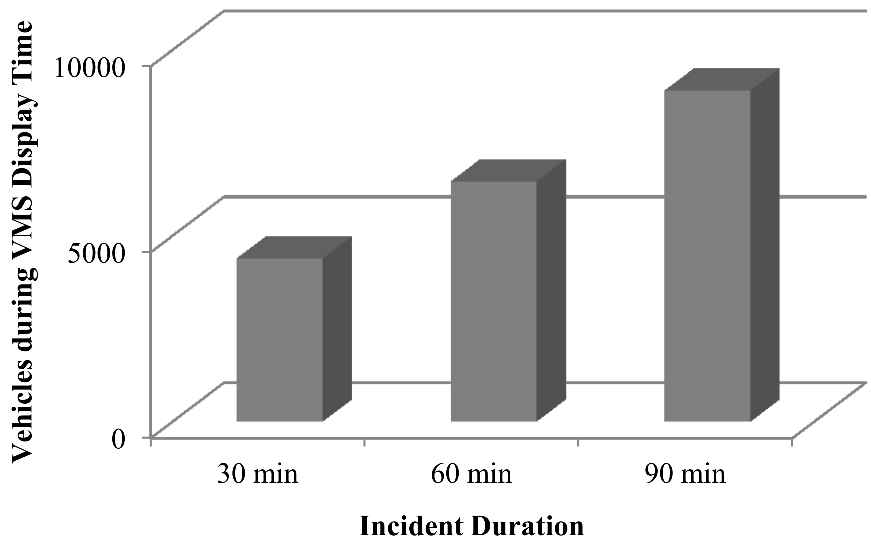


FIGURE 11 Vehicle Throughput Measurements for Location 6 during VMS Display Time and Two Simulation Hours respectively, Original and Alternate Routes Comparison



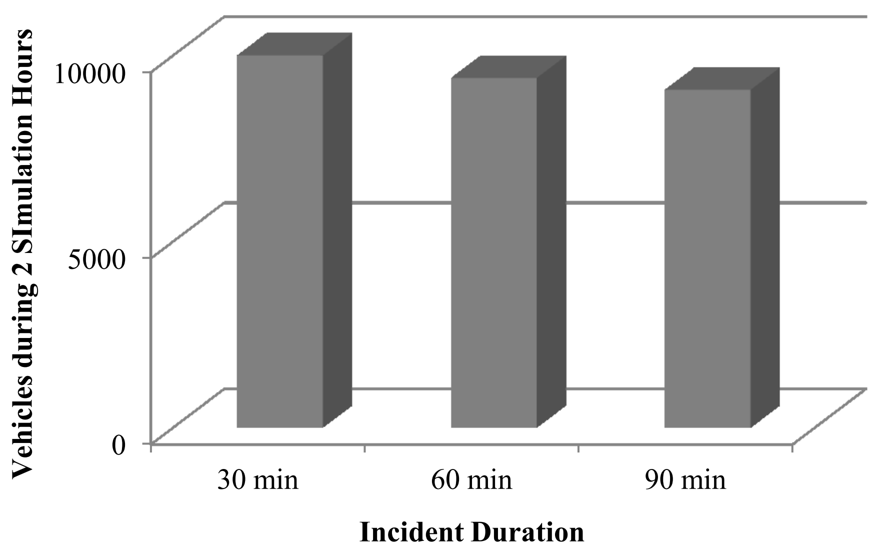


FIGURE 12 Vehicle Throughput during VMS Display Time and Two Simulation Hours as a Function of Incident Duration for Location 2, 15 minutes Response Time, 50% Lane Closure and VMS Level 2

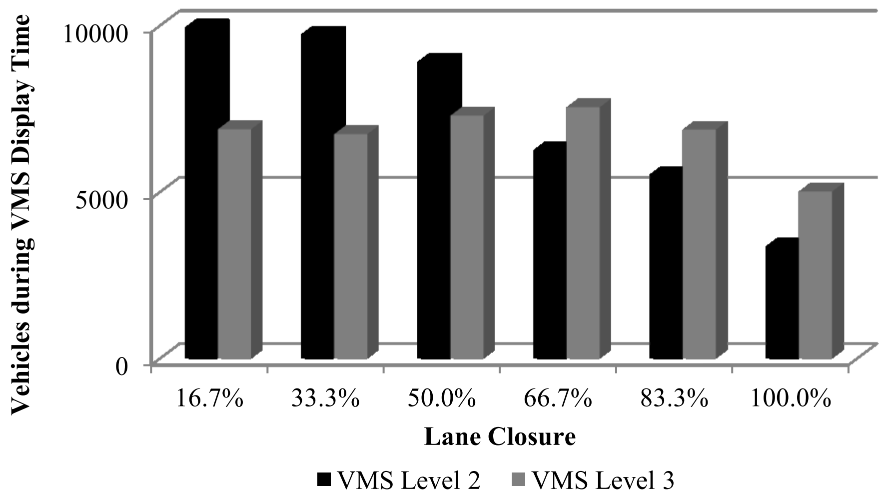


FIGURE 13 Vehicle Throughput as a Function of Lane Closure for Location 2, 90 minutes Incident Duration and 5 minutes Response Time

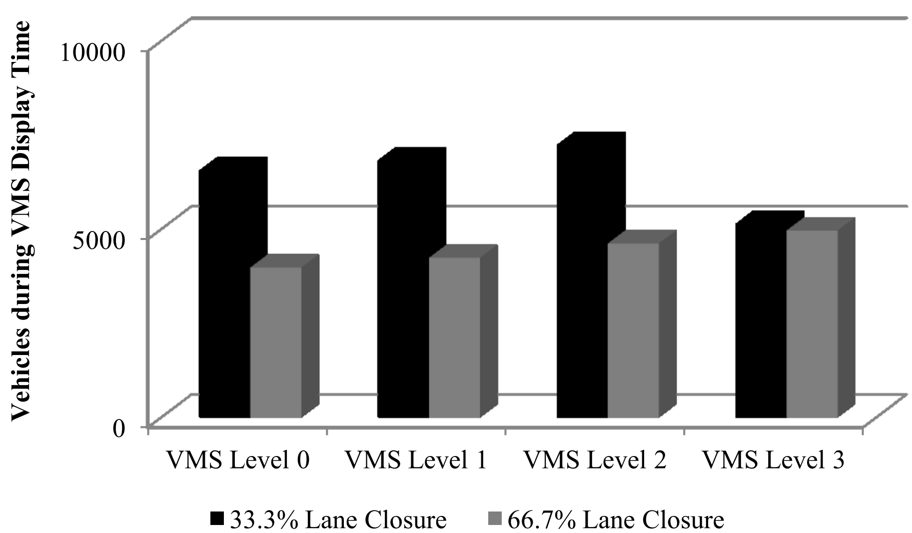


FIGURE 14 Vehicle Throughput as a Function of VMS Display Time for Location 2, 60 minutes Incident Duration and 5 minutes Response Time

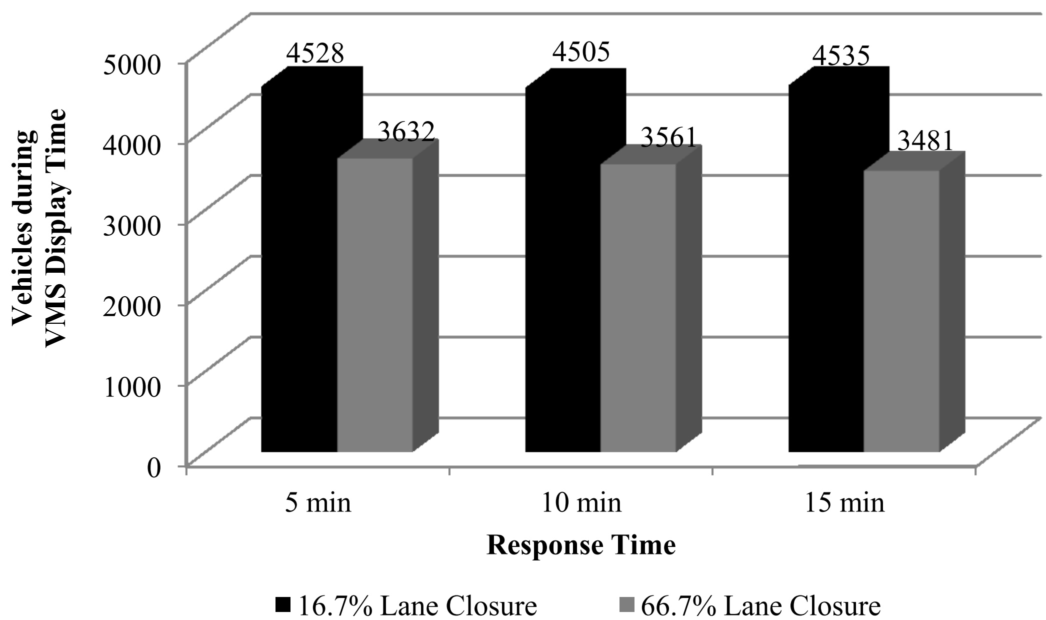


FIGURE 15 Vehicle Throughput as a Function of Response Time for Location 2, 30 minutes Incident Duration and VMS Level 2

Table 10 Vehicle Throughput for All Critical Locations and Defined Incident Conditions

Location	Lane Closure (%)	Routes	Vehicles during VMS Display			
			VMS Level 0	VMS Level 1	VMS Level 2	VMS Level 3
1	50.0	Original	1272	1220	1053	814
		Alternate	0	157	315	535
		Total	1272	1377	1368	1349
1	100.0	Original	786	807	775	805
		Alternate	0	108	268	509
		Total	786	915	1043	1314
2	50.0	Original	6129	5955	6022	3466
		Alternate	0	379	782	1758
		Total	6129	6334	6804	5224
3	40.0	Original	4857	4248	3934	3175
		Alternate	0	174	338	1147
		Total	4857	4422	4272	4322
4	66.7	Original	2664	2655	2499	2303
		Alternate	0	113	294	816
		Total	2664	2768	2793	3119
5	60.0	Original	4942	4948	4938	4962
		Alternate	0	99	277	844
		Total	4942	5047	5215	5806
6	100.0	Original	1033	1017	965	914
		Alternate	1760	1778	1792	1944
		Total	2793	2795	2757	2858
7	50.0	Original	4112	3984	3710	2227
		Alternate	0	280	984	2189
		Total	4112	4264	4694	4416
8	66.7	Original	2121	1683	1788	1950
		Alternate	0	82	233	613
		Total	2121	1765	2021	2563
9	66.7	Original	2600	2572	2597	2578
		Alternate	0	113	391	1504
		Total	2600	2685	2988	4082

Table 11 Vehicle Throughput during VMS Display Time for Location 2

Lane Closure	Incident Duration								
	30 minutes			60 minutes			90 minutes		
	Max. Vehicle Trough put	VMS Level	Response Time (min)	Max. Vehicle Trough put	VMS Level	Response Time (min)	Max. Vehicle Trough put	VMS Level	Response Time (min)
16.7	4528	2	15	7413	2	15	9952	3	15
33.3	4528	2	5	7239	2	5	9731	2	5
50.0	4461	2	5	6804	2	5	8905	2	5
66.7	3632	2	5	5129	3	15	7549	3	5
83.3	3535	2	5	5060	3	10	6878	3	5
100.0	3466	3	5	4280	3	5	5019	3	5

Table 12 Vehicle Throughput during Two Simulation Hours for Location 2

Lane Closure	Incident duration								
	30 minutes			60 minutes			90 minutes		
	Max. Vehicle Trough put	VMS Level	Response Time (min)	Max. Vehicle Trough put	VMS Level	Response Time (min)	Max. Vehicle Trough put	VMS Level	Response Time (min)
16.7	10151	2	5	10132	2	15	10140	2	15
33.3	10135	0	15	10119	1	5	9917	2	5
50.0	10121	2	5	10082	2	5	9085	2	5
66.7	10092	1	10	8368	2	5	7710	3	5
83.3	10079	1	15	8051	2	10	7025	3	5
100.0	9743	2	15	7687	3	10	5106	3	5

Table 13 Vehicle Throughput as a Function of VMS Display Time

										For VMS Display Time
		Original			Alternate			Total		
Lane closure	VMS level	VMS Display Time (min)			VMS Display Time (min)			VMS Display Time (min)`		
		20	25	30	20	25	30	20	25	30
16.7	0	4405	4405	4405	0	0	0	4405	4405	4405
	1	4388	4364	4350	123	154	179	4511	4518	4529
	2	4249	4208	4108	266	324	371	4515	4532	4479
	3	2699	2465	2357	674	815	1046	3373	3280	3403
50	0	4191	4191	4191	0	0	0	4191	4191	4191
	1	4157	4160	4157	127	154	180	4284	4314	4337
	2	4136	4134	4083	264	319	372	4400	4453	4455
	3	2725	2485	2282	658	818	1064	3383	3303	3346
										For 2 Simulation Hours
		Original			Alternate			Total		
Lane closure	VMS level	VMS Display Time (min)			VMS Display Time (min)			VMS Display Time (min)		
		20	25	30	20	25	30	20	25	30
16.7	0	10144	10144	10144	0	0	0	10144	10144	10144
	1	9991	9983	9940	123	154	179	10114	10137	10119
	2	9854	9786	9718	266	324	371	10120	10110	10089
	3	8149	8883	8477	756	891	1116	8905	9774	9593
50	0	10107	10107	10107	0	0	0	10107	10107	10107
	1	9990	9955	9920	127	154	180	10117	10109	10100
	2	9837	9779	9736	264	319	372	10101	10098	10108
	3	8443	8585	8217	743	900	1128	9186	9485	9345

4.3 Travel Times

Travel time is measured only in second and third simulation sets related to Incident Location 2. Four major routes that include this incident location are selected for travel time measurements in VISSIM. Travel time results are given in Tables 14 and 15.Traffic operators' optimal responses based on shortest travel time are given in Table 14. Table 15 presents travel time on four selected routes as a function of VMS Display Time and VMS Level.

Table 14 Travel Time Based Optimal Responses in Terms of Response Time and VMS Level for Location 2

Incident Settings		Minimum Travel Time (min)	Optimal Response	
Incident Duration	Lane Closure (%)		Response Time	VMS Level
30 min	16.7	10.71	5	2
	33.3	10.74	5	2
	50.0	11.52	5	2
	66.7	12.18	15	3
	83.3	13.77	5	3
	100.0	15.55	5	3
60 min	16.7	12.06	5	2
	33.3	12.29	5	2
	50.0	13.31	5	2
	66.7	15.12	15	3
	83.3	19.11	5	3
	100.0	27.21	5	2
90 min	16.7	12.52	5	2
	33.3	12.83	5	2
	50.0	14.26	5	2
	66.7	17.32	15	3
	83.3	25.79	5	3
	100.0	34.54	5	3

Table 15 Travel Times as a Function of VMS Display Time and VMS Level for Four Selected Routes on the Test Network

Location	Lane Closure (%)	VMS level	With Signal Delay			Without Signal Delay		
			VMS Display Time (min)			VMS Display Time (min)		
			20	25	30	20	25	30
I-15 SB from 600 S to 4500 S	16.7	0	9.30	9.30	9.30	9.30	9.30	9.30
		1	8.94	9.09	8.92	8.38	7.86	7.83
		2	8.74	8.76	8.65	7.92	7.86	7.73
		3	9.97	10.20	10.98	9.65	10.46	10.95
	50	0	11.08	11.08	11.08	11.08	11.08	11.08
		1	10.89	10.37	10.31	8.64	8.71	8.22
		2	10.52	9.75	9.72	8.48	8.24	8.03
		3	10.09	10.01	11.04	10.02	10.62	11.13
SR 201 EB @ 3400 W to I-15 SB @ 4500 S	16.7	0	11.40	11.40	11.40	11.40	11.40	11.40
		1	11.11	11.05	10.87	11.66	10.71	10.55
		2	10.85	10.82	10.65	10.72	10.71	10.56
		3	10.83	11.96	12.36	10.15	10.40	11.22
	50	0	11.95	11.95	11.95	11.95	11.95	11.95
		1	12.35	11.27	11.43	12.20	11.66	11.19
		2	11.62	11.09	11.03	11.64	11.30	11.19
		3	11.53	11.58	12.89	10.18	10.71	11.57
I-80 WB @ 1300 E to I-15 SB @ 4500 S	16.7	0	10.90	10.90	10.90	10.90	10.90	10.90
		1	10.44	10.24	10.36	10.29	9.69	9.60
		2	9.81	9.62	9.67	9.43	9.27	9.09
		3	9.08	10.19	11.14	9.25	10.22	11.02
	50	0	11.60	11.60	11.60	11.60	11.60	11.60
		1	11.76	11.06	11.13	10.49	10.31	9.92
		2	11.20	10.51	10.42	9.79	9.55	9.34
		3	9.82	10.48	11.04	9.20	10.06	10.74
I-80 @ Parleys to I-15 SB @ 4500 S	16.7	0	15.34	15.34	15.34	15.34	15.34	15.34
		1	14.71	14.57	14.70	14.87	14.15	14.08
		2	14.34	14.07	14.01	13.93	13.81	13.54
		3	13.48	15.20	16.11	13.88	15.36	16.84
	50	0	16.02	16.02	16.02	16.02	16.02	16.02
		1	16.13	15.35	15.38	14.85	14.78	14.44
		2	15.71	15.15	14.85	14.31	14.09	13.81
		3	14.52	15.43	16.64	13.68	15.03	16.13

4.4 Network Performance

Network performance results come from network performance evaluation in VISSIM. Network delay accounts for incident induced delay on the freeways, VMS induced delay on arterial routes and signal timing induced delay on arterial routes. Network performance results are given in Tables 16-20 and Figures 16-19. Results in Tables 16-18 represent total network delay are given for all incident locations, for fixed Incident Duration, Lane Closure, and Response Time. Tables 19-20 present optimal response in terms of traffic operators' Response Time and VMS Level, for Location 2 only. Figures 16-19 present more detailed findings related to Location 2. These figures provide the insight into the impact of Incident Duration, Lane Closure, Response Time, and VMS Level on network wide delay. The purpose was to determine optimal traffic operators' responses on the network wide level. These results provide not only the insight into incident impacts on the freeways, but on the arterial network as well.

Table 16 Total Network Delay for All Incident Locations and Defined Incident Settings

Location	Lane Closure %	Total Delay Time (hr)			
		VMS Level 0	VMS Level 1	VMS Level 2	VMS Level 3
1	50.0	6273	6332	6486	6241
1	100.0	7265	7034	7099	6648
2	50.0	8021	7725	6928	9940
3	40.0	6552	8063	8470	8494
4	66.7	6798	6708	6698	6586
5	60.0	9175	9436	9093	7932
6	100.0	8929	8840	8773	8787
7	50.0	6700	6726	6508	7724
8	66.7	7708	8146	7861	7302
9	66.7	11884	12066	11604	10525

Table 17 Average Delay Time per Vehicle on the Network Wide Level for All Incident Locations and Defined Incident Settings

Location	Lane Closure %	Average Delay Time per Vehicle (min)			
		VMS Level 0	VMS Level 1	VMS Level 2	VMS Level 3
1	50.0	2.67	2.69	2.76	2.66
1	100.0	3.11	3.01	3.03	2.83
2	50.0	3.41	3.28	2.94	4.25
3	40.0	2.78	3.42	3.60	3.62
4	66.7	2.90	2.87	2.86	2.81
5	60.0	3.90	4.01	3.86	3.37
6	100.0	3.79	3.76	3.73	3.74
7	50.0	2.85	2.86	2.76	3.29
8	66.7	3.30	3.49	3.36	3.12
9	66.7	5.08	5.15	4.96	4.49

Table 18 Average Number of Stops per Vehicle for All Incident Locations and Defined Incident Settings

Location	Lane Closure %	Average Number of Stops per Vehicle			
		VMS Level 0	VMS Level 1	VMS Level 2	VMS Level 3
1	50.0	7.67	7.76	8.11	7.54
1	100.0	8.40	8.51	8.74	8.01
2	50.0	11.96	11.24	8.62	20.89
3	40.0	8.26	15.09	17.23	17.69
4	66.7	9.30	9.04	9.10	8.52
5	60.0	13.96	14.64	13.60	10.59
6	100.0	10.76	10.47	10.47	10.77
7	50.0	8.35	8.41	7.87	12.55
8	66.7	11.24	12.62	11.49	10.00
9	66.7	17.43	17.55	16.64	15.99

Table 19 Optimal Response in Terms of Response Time and VMS Level with Respect to Network Wide Delay for Location 2

Lane closure	Incident duration								
	30 minutes			60 minutes			90 minutes		
	Network wide delay	VMS level	Response time	Network wide delay	VMS level	Response time	Network wide delay	VMS level	Response time
16.7	6347	2	5	6497	2	5	6546	2	5
33.3	6457	2	5	6658	2	15	6719	2	5
50.0	6618	2	15	6928	2	5	7574	2	15
66.7	7677	2	10	9577	2	5	10676	3	5
83.3	8234	2	15	10788	2	5	11937	3	5
100.0	9328	2	5	12683	3	5	14558	3	5

Table 20 Network Performance as a Function of VMS Display Time for Location 2

Lane Closure (%)	VMS Level	Total Delay (h)			Average Number of Stops			Average Speed (mph)		
		VMS Display Time (min)			VMS Display Time (min)			VMS Display Time (min)		
		20	25	30	20	25	30	20	25	30
16.7	0	6693	6693	6693	8.34	8.34	8.34	46.32	46.32	46.32
	1	6498	6445	6474	7.91	7.77	7.86	46.63	46.68	46.59
	2	6561	6605	6545	8.06	8.10	8.08	46.50	46.42	46.49
	3	8727	7743	7998	13.25	12.20	16.74	44.20	44.60	43.07
50	0	6878	6878	6878	8.42	8.42	8.42	46.02	46.02	46.02
	1	6793	6738	6823	8.35	8.07	8.23	46.09	46.23	46.14
	2	6728	6760	6621	7.99	8.31	8.07	46.39	46.16	46.23
	3	8498	8335	8330	14.45	14.30	15.32	43.70	43.71	43.45

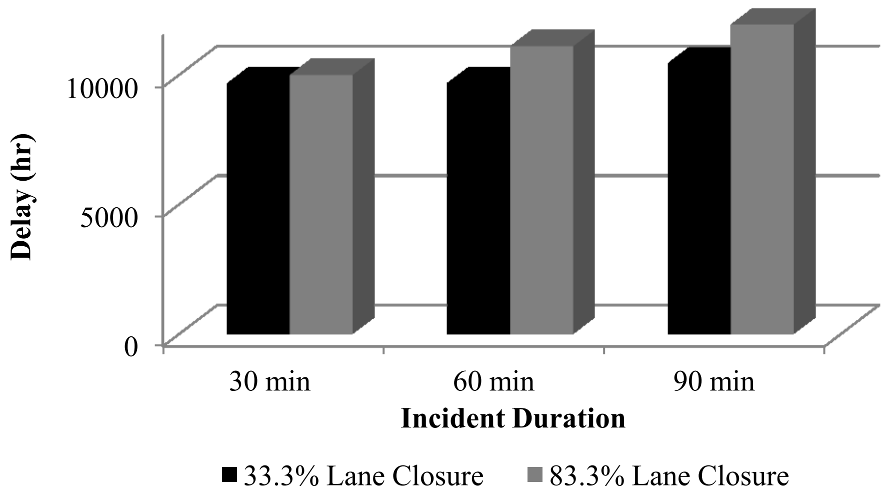


FIGURE 16 Network Wide Delay as a Function of Incident Duration for Location 2, 5 minutes Response Time and VMS Level 3

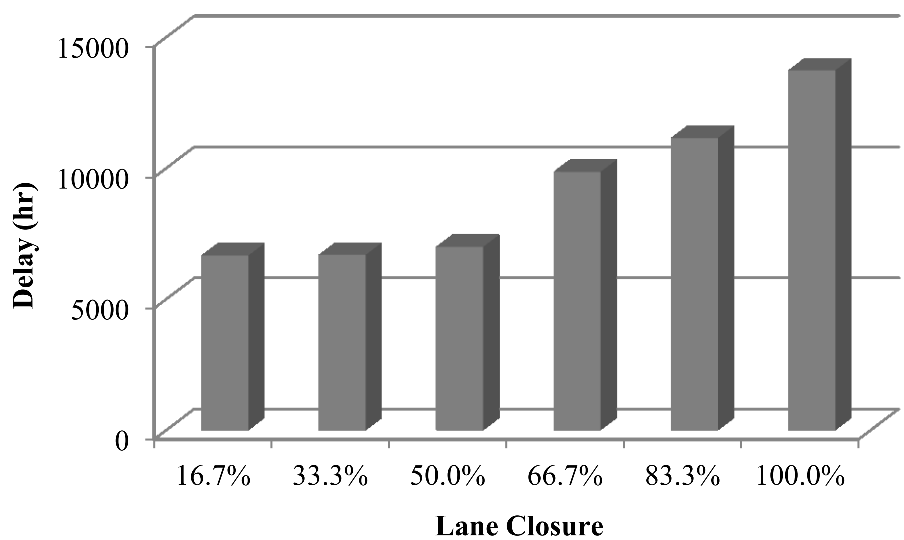


FIGURE 17 Network Wide Delay as a Function of Lane Closure for Location 2, 60 minutes Incident Duration, 10 minutes Response Time and VMS Level 2

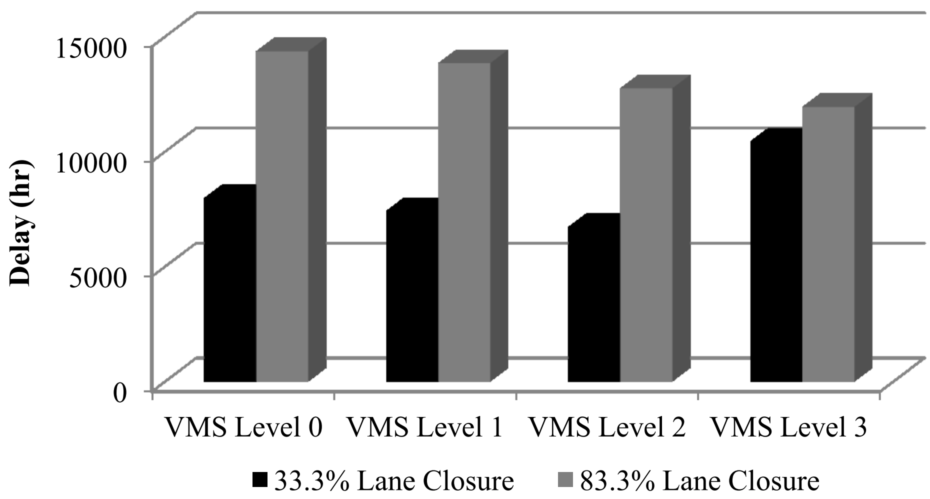


FIGURE 18 Network Wide Delay as a Function of VMS Level for Location 2, 90 minutes Incident Duration and 5 minutes Response Time

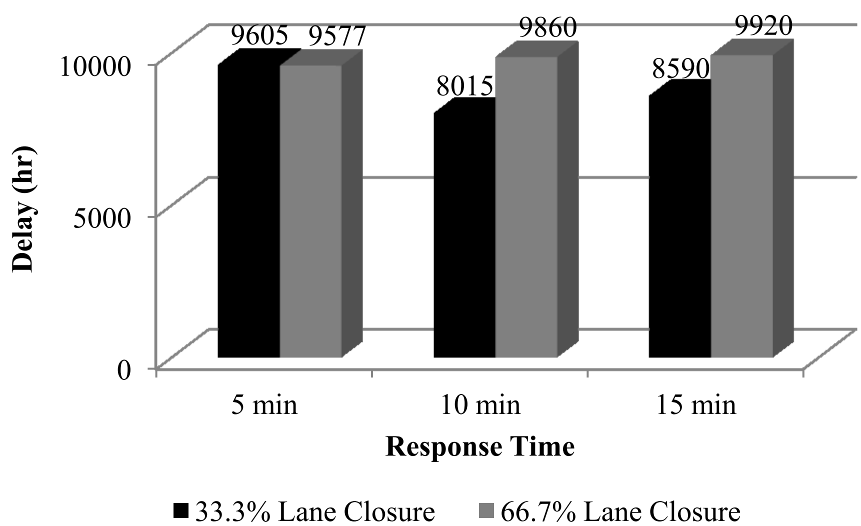


FIGURE 19 Network Wide Delay as a Function of Response Time for Location 2, 60 minutes Incident Duration and VMS Level 2

CHAPTER 5

DISCUSSION

This chapter discusses the results presented in the previous chapter. Results are discussed in the same order as they are presented, in four groups: aggregate freeway delay, vehicle throughput, travel times, and network performance. Within each of these four groups, tables and figures are discussed in the same order as they are presented in the Results, from the first to the third simulations set.

5.1 Aggregate Freeway Delay

The first simulation set provides aggregate freeway delay values as a function of Incident Location, Lane Closure and VMS Level, while other variables are kept constant. Freeway delay is measured for defined Lane Closure for each Incident Location. Table 6 shows how aggregate freeway delay changes with VMS Level for each location and defined Lane Closure. Table 7 shows average delay on the freeways per vehicle.

Freeway delay should decrease as the number of rerouted vehicles increases with higher VMS Levels, and this is the case for all locations except for location 5. Among all locations, location 5 has the highest demand and three out of five lanes closed which causes 80% capacity reduction. This is why changes in VMS Level do not contribute to delay reduction, and make less significant impact on delay changes when compared to other locations. For all locations with Lane Closure higher than 50% changes in VMS

Level affect delay less when compared to locations with Lane Closure 50% or lower. Location 3 was tested for the lowest Lane Closure and the results show that it is enough to implement VMS Level 1 to reduce the delay.

Location 9 has 50% higher delay results than location 8 for all VMS Levels, even though the demand, number of lanes and Lane Closure are the same for these two locations. Figure 4 shows the comparison of freeway delay for these two locations. Explanation for this could be the way the demand is distributed during the simulated PM peak period for two different locations. The optimal VMS Level is the same for both locations.

Results from the first simulation set indicate that in general higher VMS induced diversion rates will reduce freeway delay. But the overall impact of VMS Level on delay reduction depends on the demand and Lane Closure. The higher the Lane Closure is, the lower the impact of VMS message content on diversion will be. Delay also depends on the demand distribution over the observed period. Different locations will show different delay results even when demand and incident conditions appear to be the same. The reason for this is that there are many other factors that could influence the ultimate delay results, such as VMS location, the number of alternate routes, whether the peak demand occurs during the incident or before/after the incident. Only higher percentages of Lane Closure are considered here, so conclusions about less severe incidents cannot be made.

The second simulation set provides more detailed insight into aggregate freeway delay as a function of Incident Duration, Lane Closure, Response Time and VMS Level. These variables determine incident/response scenarios tested on Incident Location 2. The purpose of this analysis was to find optimal response in terms of Response Time and VMS Level, for each combination of Incident Duration and Lane Closure.

In the case of aggregate freeway delay, optimal response is the combination of parameters that results in the lowest delay. Table 8 shows only optimal responses for each combination of variables that define incident conditions. Complete results, showing the aggregate freeway delay for the all combinations of incident and response settings for location 2, are in Appendix B.

Results from Table 8 show how the lowest freeway delay in most cases results from the lowest Response Time and the highest VMS Level, with some exceptions where optimal Response Time is higher than minimal. These results are expected because lowest freeway delay should happen when the highest number of vehicles diverts from the freeways. On the other hand, aggregate freeway delay should increase with Incident Duration and Lane Closure. Some results from Table 8 disagree with this and show lower delay with Incident Duration or Lane Closure increase. These results should be taken with the reserve. What follows is the analysis of aggregate freeway delay from the second simulation set that explains the impact of each variable separately.

Figure 5 shows the impact of Incident Duration on aggregate freeway delay for two different incident/response scenarios. The first scenario is an incident with 16.7% Lane Closure, with 5 minutes Response Time and VMS Level 1. For this scenario, aggregate freeway delay increases with Incident Duration increase. This is how delay changes as a function of Incident Duration in most cases. However, the second scenario in Figure 5, with 50% Lane Closure, 15 minutes Response Time and VMS Level 3 is an example of rare and unexpected results, where delay decreases as Incident Duration increases.

Although this could happen, the final recommendations should not be based on these unexpected results because during the peak period it is much more likely to see the cases similar to the first scenario described here. Figure 6 shows a general dependence between Lane Closure and aggregate freeway delay, where delay increases with Lane Closure.

To consider the influence of variables that define incident response, aggregate freeway delay is also presented as a function of VMS Level and Response Time. Figure 7 shows aggregate freeway delay as a function of VMS Level for two scenarios that differ in terms of Lane Closure. In both cases, for 33.3% and 83.3% Lane Closure delay reaches its minimum value for VMS Level 3 and the highest traffic diversion rate. The only difference between the two cases is that the delay values are much higher for higher Lane Closure. Figure 8 shows aggregate freeway delay as a function of Response Time for 33.3% lane Closure, VMS Level 1 and Incident Durations of 30 and 60 minutes. If we compare Figures 7 and 8, the impact of Response Time looks less significant than the impact of VMS Level. No general conclusion can be made about the impact of Response Time for less severe incidents. For incidents that last longer with more lanes closed the freeway delay will increase as Response Time increases.

The final set of simulations had the purpose to indicate the impact of VMS Display Time. Table 9 shows aggregate freeway delay in hours for different response combinations to incidents with 1/6 and 3/6 Lane Closure. The optimal VMS Display Time would be the one that results with minimum delay value for given incident settings. When one lane out of six is closed, the VMS Display Time that results in the lowest delay would be 20 minutes in combination with the highest VMS Level 3. When 3 lanes are closed, the optimal VMS Display Time, according to the results, is 25 minutes. However, the table shows that for VMS Level 3 and 25 minutes Display Time, freeway delay is much higher for less severe incidents (172 hours for 1/6 lanes closed), when compared to the delay for more severe incidents (60 hours for 3/6 lanes closed). This would be a good reason to take a closer look at the delay distribution over the simulation time for the further comparison of these two results.

Figure 9 shows that the overall delay is higher for the less severe incident but towards the end of the simulation time. On the time axis, the incident lasts from 4:10 PM to 4:40 PM. On this portion of time axis there is almost no difference between the two incidents in terms of average freeway delay. The reason for this is a high diversion rate. Once the incident is cleared and VMS Level 3 is off, the number of vehicles on the segment where incident occurred will increase by 40 to 80%, which explains the way average delay is distributed. The explanation for higher delay for less severe incident in this case could be in the distribution of vehicle arrivals within the two hours of simulation.

For both incident types, the optimal VMS Display Time reduces delay when compared to the longest examined VMS Display Time. When 1/6 lanes is closed, the optimal VMS Display Time of 20 minutes means 73% lower freeway delay when compared to the longest VMS Display Time of 30 minutes. When 3/6 lanes are closed, optimizing VMS Display Time rather than simply choosing the longest time, brings 56% savings in freeway delay.

The analysis of aggregate freeway delay based on three simulation sets shows the impacts of different variables. Freeway delay will change in a different manner for the same incident settings depending on the Incident Location. Generally, delay increases as Incident Duration and Lane Closure increase. Delay decreases when higher VMS Levels are implemented. No general conclusions can be made about the impact of Response Time for less severe incidents, while for more severe incidents delay increases as Response Time increases. Finally, delay can be reduced significantly if optimal rather than the highest VMS Display Time is chosen.

5.2 Vehicle Throughput

Vehicle throughput is measured in three simulation sets, during the time VMS is on and the entire simulation time, for original and alternate routes. The results showing the number of vehicles bypassing the incident site for all Incident Locations during the two simulation hours are in Table 10. Vehicle throughput here is a function of Incident Location, Lane Closure, and VMS Level. Higher vehicle throughput means that higher number of vehicles managed to pass the incident site, while lower values indicate that higher number of vehicles is waiting in line during the incident. Maximum total vehicle throughput should indicate the optimal VMS Level for defined incident conditions at each location.

The vehicle throughput for location 1, from Table 10 results, is higher when half of the through lanes are closed for 60 minutes during the simulation period, than when all lanes are closed. As shown in Figure 10, the optimal VMS for 50% Closure is Level 1, and for full closure Level 3. This means that the optimal response depends on the Lane Closure, but also indicates that for less severe incidents lower diversion rates might be beneficial. For both locations 1 and 6, for which defined Lane Closure is 100%, the optimal VMS from vehicle throughput perspective is Level 3. However, the change in VMS message content for these two locations does not change the vehicle throughput as much as it would change it if the Lane Closure was lower. In the case of location 4, less than half of the through lanes are closed and the highest vehicle throughput is obtained when no VMS message is displayed. For all other locations, more than half through lanes are closed and VMS Level 3 results in the highest vehicle throughput.

With the increase of VMS Level diversion rates increase, and the vehicle throughput increases on the alternate routes and might decrease on the original routes, depending on the vehicle arrivals. Figure 11 shows how with higher VMS Levels, vehicle throughput generally increases on the alternate routes and decreases on the original routes, during both VMS Display Time and the entire simulation period of two hours.

A more in depth analysis comes from the second set of simulations where vehicle throughput is measured as a function of Incident Duration, Lane Closure, Response Time and VMS Level. Only optimal combination of Response Time and VMS Level for each combination of Incident Duration and Lane Closure is presented in Tables 11 and 12. Table 11 shows vehicle throughput during VMS Display Time, while Table 12 shows vehicle throughput for the entire simulation period. Complete results that include all incident/response scenarios are in Appendix B. Both Tables 11 and 12 show how the most intensive VMS messages and the quickest response might not be beneficial for some types of incidents.

Figure 12 shows vehicle throughput as a function of Incident Duration for the same incident scenario, but measured during VMS Display Time only and during the two hours of simulation. The graph that shows vehicle throughput while VMS message is displayed increases with Incident Duration. This is because the longer the incident is the longer the VMS is displayed, and vehicle throughput is measured for the longer time period. But on the level of two simulation hours, it is clear that vehicle throughput decreases as Incident

Duration increases. So the conclusions about the way different variables influence vehicle throughput must be based on the entire simulation period.

An example of the impact of Lane Closure on vehicle throughput for two different VMS Levels is in Figure 13. While for VMS Level 2 vehicle throughput decreases as Lane Closure increases, for VMS Level 3 vehicle throughput shows less regular value changes but drops when all lanes are closed. The impact of VMS Level also needs to be discussed, and it is given in Figure 14. For lower Lane Closure of 33.3%, it is not the highest diversion rate that results in best vehicle throughput. For higher Lane Closure of 66.7%, VMS Level 3 provides the best throughput. The results show interaction between Lane Closure and VMS Level. If VMS Level is changed for the same Lane Closure, the value of Vehicle throughput will change. But the optimal response strategies should be determined for variables that define the incident, in terms of variables that define the response. So, the impact of Lane Closure on optimal VMS Level is more important for this research.

From Figure 15, the impact of Response Time is less significant than the impact of VMS Level (Figure 14). The optimal response will depend more on the nature of response than the operators' responsiveness. However, when more than half of through lanes are closed, quicker response is a better option in terms of vehicle throughput.

The third simulations set measured vehicle throughput as a function of VMS Display Time. Table 13 shows vehicle throughput for two hours of simulation period for original routes only and total throughput for original and alternate routes. Vehicle throughput for original routes indicates the change in traffic volumes on the freeways as a function different VMS Levels and VMS Display Times. Higher VMS Display Time results in lower vehicle throughput for the freeways because vehicles have more time to divert. Total number of vehicles on original and alternate routes should indicate the optimal incident response. For both tested incident types, with 1/6 and 3/6 Lane Closure, the highest VMS Display Time does not result in the highest number of vehicles passing the incident site. Table 13 also shows that the change in vehicle throughput is more significant when VMS Level Changes than when VMS Display Time changes. Change in VMS Display Time has the greatest impact for the highest VMS Level.

Summary on vehicle throughput analysis would be that for each location best throughput depends on the Lane Closure. Optimal response in terms of Response Time and VMS Level also depends on the Lane Closure and Incident Duration. For more severe incidents, higher VMS Level and lower Response Time result in better vehicle throughput. For less severe incidents, with less than half through lanes closed, choosing the strongest response is not always the best option.

5.3 Travel Time

The second and third simulation sets included travel time measurements on four major routes for Incident Location 2. These routes are defined along the freeways. The second simulations set measured travel time as a function of Incident Duration, Lane Closure, Response Time and VMS Level. Table 14 shows only optimal responses for all simulated incident conditions. Travel time is averaged for the four measurement routes. The responses that provided minimum average travel time are considered to be optimal. As expected, travel time increases for incidents that last longer with more through lanes closed. In almost all cases, 5 minute Response Time is the best option to minimize the travel time. When four out of six lanes are closed, best Response Time is 15 minutes, because the change in VMS Level allows for the longer time to display VMS message. Optimal VMS Level shows dependence on the Lane Closure, and when more than half of through lanes are closed VMS Level 3 is the best option.

Table 15 shows travel time measurements as a function of VMS Display Time, with and without the presence of traffic signals on the arterial routes. The results for VMS Level 0 are the same regardless of the traffic signal presence because vehicles do not use arterial routes in this case. Overall results show that the presence of traffic signals slightly increases the travel time. This increase is not significant in most cases, since traffic signals are coordinated on the considered corridors. Similarly to vehicle throughput results, the impact of VMS Display Time on travel time is less significant than the impact of VMS Level. For both 1/6 and 3/6 Lane Closure, the results that include traffic signal timing sometimes show minimum travel time values for VMS Display Time lower than 30 minutes. However, these are only the results for four routes and conclusions about VMS Display Time cannot be based only on these results.

The travel time on the freeways increases as incidents become more severe. For incidents where less than 50% lanes are closed, in order to minimize the travel time, response in terms of VMS message content and duration of message display should be optimized. Choosing simply VMS Level 3 and the longest Display Time will not always result in minimal travel time.

5.4 Network Performance

Network performance measures acount for delays that freeway traffic causes on the arterial routes. These measures should indicate what the best response is for different incident conditions on the network wide level.

Tables 16 – 18 show three network performance measures: total delay, average delay per vehicle, and average number of stops per vehicle. For the first set of simulations these measures are a function of Incident Location, Lane Closure and VMS Level. Just as the results for vehicle throughput show, the highest VMS Level is not always the best response and the optimization of diversion rates is required in order to minimize total network delay. Delay values in Table 16 also show that for the same Levels of Closure optimal VMS Level differs for different locations. So the optimal incident response is location dependent.

Table 19 shows the total network delay results from the second simulations set. Delay is a function of Incident Duration, Lane Closure, Response Time and VMS Level. For most incidents that last up to 60 minutes, VMS Level 2 results in the best delay values. Results for all combinations of considered variables are not discussed in this paper. Some interesting findings are extracted and presented in Figures 17 – 19 to show the effects of each variable on network wide delay. Complete results are in Appendix B.

Figure 17 shows network wide delay as a function of Incident Duration for two scenarios with different Lane Closure. Incident Duration increase will cause the delay to increase, regardless of Lane Closure. Figure 18 is an example of Lane Closure impact while other variables are kept constant, and the delay increases with the number of lanes closed. These results are expected, because more severe incidents cause more serious delay on both freeway and network wide level.

Figure 18 shows network wide delay as a function of VMS Level for incidents with two different Lane Closures. This figure shows some counterintuitive findings for less severe of the two compared incidents. When two out of six through lanes are closed, stronger response strategies increase the network wide delay. In this case implementing VMS Level 3 instead of optimal VMS Level 2 would cause the network delay to increase by 55%. When five out of six through lanes are closed, the highest VMS Level will result in minimum network delay.

Figure 19 shows the impact of Response Time on network wide delay for incidents with two different Lane Closures. For more severe incident quickest response should be implemented to minimize the delay. For less severe of the two compared incidents, when two out of six through lanes are closed, Response Time of 10 minutes gives minimum delay value. Responding five minutes earlier would increase the delay by 20%, while responding five minutes later results in 7% delay increase.

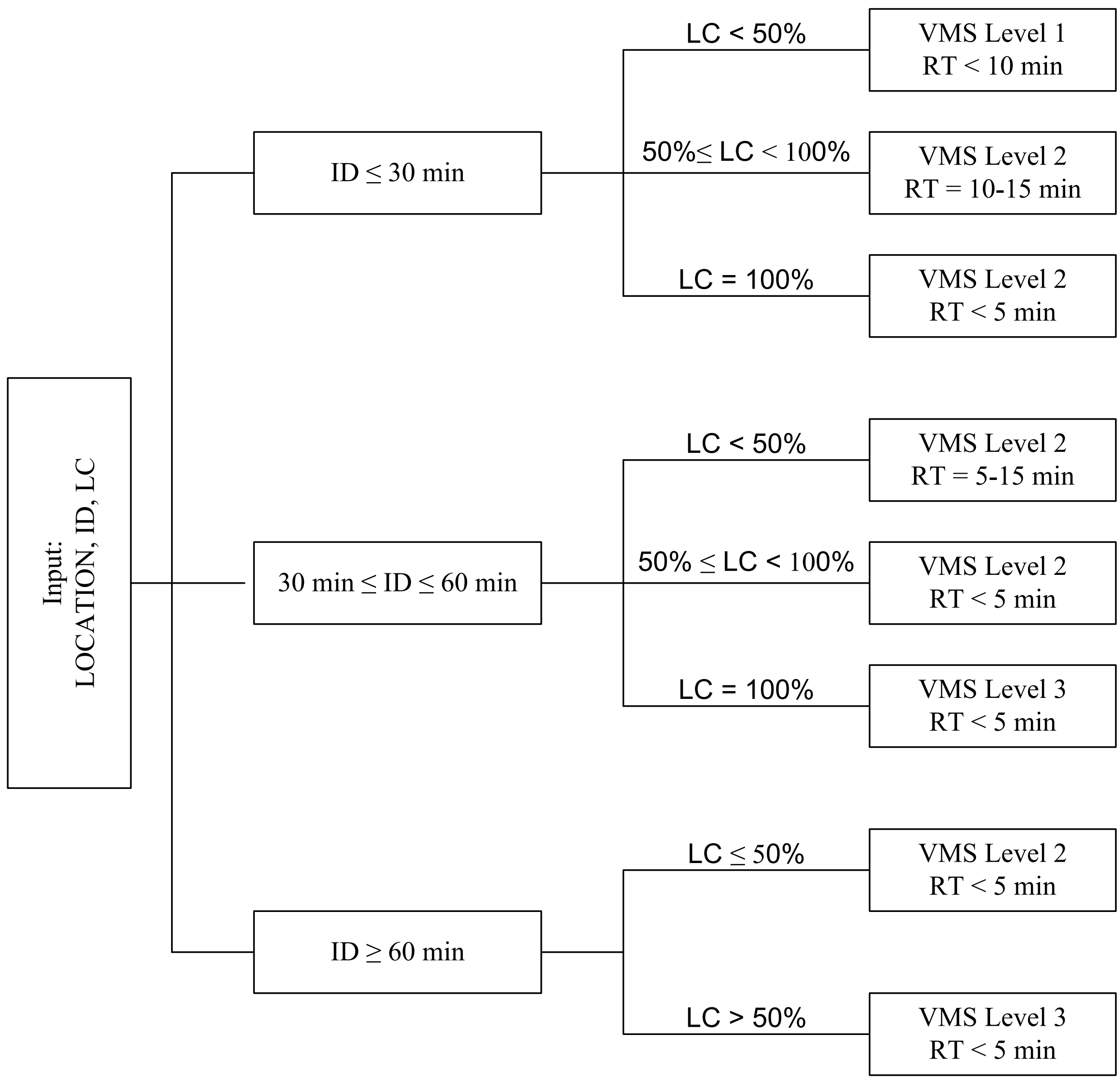
Table 20 shows network performance results from the third simulation set. Three network performance measures: total delay, average number of stops and average speed are a function of VMS Display Time. If we look at the results for 1/6 Lane Closure, the optimal response is the combination of VMS Level 1 and VMS Display Time 25 minutes. Both network delay and average number of stops show that this would be the optimal response. Increasing or decreasing VMS Display Time for VMS Level 1 would bring 29 or 53 hours increase in delay, respectively. This would be less than 1% delay increase on the network wide level. For VMS Level 2, the best response comes with the highest VMS Display Time, again with less than 1% delay increase if VMS Display Time is different than optimal. However, for VMS Level 3 choosing VMS Display Time of 20 instead of 25 minutes increases network delay by 13%. Choice of VMS Display Time of 30 minutes increases network delay by 3%.

For more severe incidents and 3/6 Lane Closure, the optimal response would be VMS Level 2 and VMS Display Time 30 minutes. Again, both network delay and average number of stops indicate this. Decreasing VMS Display Time by 5 minutes would result in 2% delay increase. The same increase in the network delay would occur if other than optimal VMS Display Time is chosen for VMS Levels 1 and 3. As in the case with other output results, the values for VMS Level 0 are the same since the vehicles do not use alternate routes.

The analysis of network performance shows that the optimal incident response in terms of network delay depends on the Incident Location. Detailed results from a single location show that delay on the network wide level increases with incident severity. Optimal response on the network wide level depends on how long the incident lasts and how many through lanes are closed. For less severe incidents that last up to 30 minutes with less than 50% Lane Closure, optimizing response in terms of VMS message content and Display Time can be more beneficial than simply choosing the strongest response.

5.5 Discussion Summary

Figure 20 summarizes the discussion. These recommendations are based on the analysis of output results for all combinations of incidents and responses. The recommended decisions are applicable to analyzed network during peak hour incidents.



ID – Incident Duration; LC – Level of Lane Closure; RT – Response Time

FIGURE 20 Recommendations for TOC Decisions during Peak Hour Incidents

CHAPTER 6

CONCLUSIONS

This chapter starts with the most important recommendations based on the analysis of the obtained results. Then it presents the contributions of the research, considering defined research goal and objectives, reviewed literature and developed methodology and results. The purpose is to explain the possibilities of practical implementation and further improvement of the presented work.

6.1 Recommendations and Contributions

This research evaluates the performance of different response strategies for defined incident conditions in order to select the strategies giving optimal results. The methodology described here is developed to assess what variables are relevant in the process of incident response, and how those variables are related to each other.

The analysis of incidents on the critical locations shows that optimal response to an incident depends on incident location. For all analyzed locations, more severe incidents require stronger responses. The set of critical locations are those that are the most complex, in terms of incident management. These locations vary in traffic volumes, number of lanes, alternate routes, and VMS availability. The locations analyzed in this paper could be used for the purpose of TOC advanced operators training as the most challenging locations. This would enable operators to deal with difficult TIM tasks in reality.

A more detailed analysis of Location 2 gives the insight into the complexity of incident response that is here represented through operators' responsiveness, VMS content and display time. Comparison of delay values for different incident conditions distinguishes two groups of incidents. The first group includes major incidents where the delay could decrease only if the intensity of response increases. These incidents last an hour or longer or have more than 1/3 of through lanes closed. The second group consists of minor incidents that last about 30 minutes and have less than 1/3 of through lanes closed. For these incidents too much response might cause greater delay than not responding at all. This indicates the need for further incident response optimization. The following recommendations for relevant decision makers result from this research:

- Categorization of traffic incidents according to their severity is a good guidance for making the decision about the appropriate response strategy
- Decision about VMS message content should include consideration of VMS Display Time for all incident types
- For less severe incidents with lower Lane Closures, more detailed messages displayed for a longer time could increase travelers' delay on both freeways and arterial routes
- All of the above applies only if good signal timing coordination on the arterial routes is maintained

Real incident response includes more than three variables. However, the contribution of this research is that it introduces the impact of VMS Display Time as a part of incident response. VMS Display Time is determined by Response Time – the shorter the Response Time is, the longer the message will be displayed. For minor incidents, displaying VMS message for too long could have negative effects. The discussed results show that the optimization of VMS Display Time primarily brings time savings on the level of freeway network. While VMS Display Time shows some impact on vehicle throughput and travel times, the impact of VMS Level is more significant. The results on the network wide level show that VMS Display Time has greater influence on the network delay for less severe incidents. Overall conclusion from the given analysis is that the optimal response to an incident, especially if Lane Closure is lower than 50%, should come from the optimization of both VMS message content and VMS Display Time. TOC operators need to consider both aspects of VMS to avoid the potential negative impacts of VMS induced diversion.

The analysis of various response strategies shows the importance of proper VMS operation and efficient use of other TOC resources. The values of delay for different combinations of variables indicate the consequences of TOC over/under-response to traffic incidents. It is important to provide an adequate training for TOC operators that deal with TIM problems. Final recommendations provided here could first be deployed for the purpose of TOC training. Recommended strategies are related to critical incident conditions, locations difficult for traffic management in peak hour period for incidents that require quick response or preliminary knowledge about the response. So the presented set of strategies or ready-to-use decisions is also a tool that could work when no time is available to run the decision support in TOC.

6.2 Future Research

Future research on this topic should include different combinations of presented variables for other critical locations in order to find optimal incident management strategies for each location individually. Even more important is to focus on the minor group of incidents for which the operators' over-reaction results in delay increase. Further research needs to account for background arterial traffic conditions and consider traffic signal timing optimization.

The major limitation of this research comes from the assumptions made about traffic diversion rates for various VMS Levels. VMS impact modeling presented here is mostly survey-based and comes from the previous research. The reason for this is the lack of up to date research on VMS in general. There is a need for further, more detailed and accurate research methodologies for modeling the impacts of VMS.

The possibility for further development of built models could be the greatest potential of the research. The methodology presented here is very convenient for the inclusion of new parameters and does not require all performed simulations to be repeated. For example, the future work and improvements of this research could include ramp metering as a new variable. The obtained results indicate where changes in TOC operators' incident response could be made so it is possible to focus only on certain types of incidents instead of re-testing all scenarios. The way the methodology is developed enables quick adjustment of given recommendations for operators' training environment. This would be a good way to verify the recommended decisions and consider their implementation in the real-life incident management.

APPENDIX A

DIVERSION RATES FOR ORIGINAL AND ALTERNATE ROUTES IN VISSIM

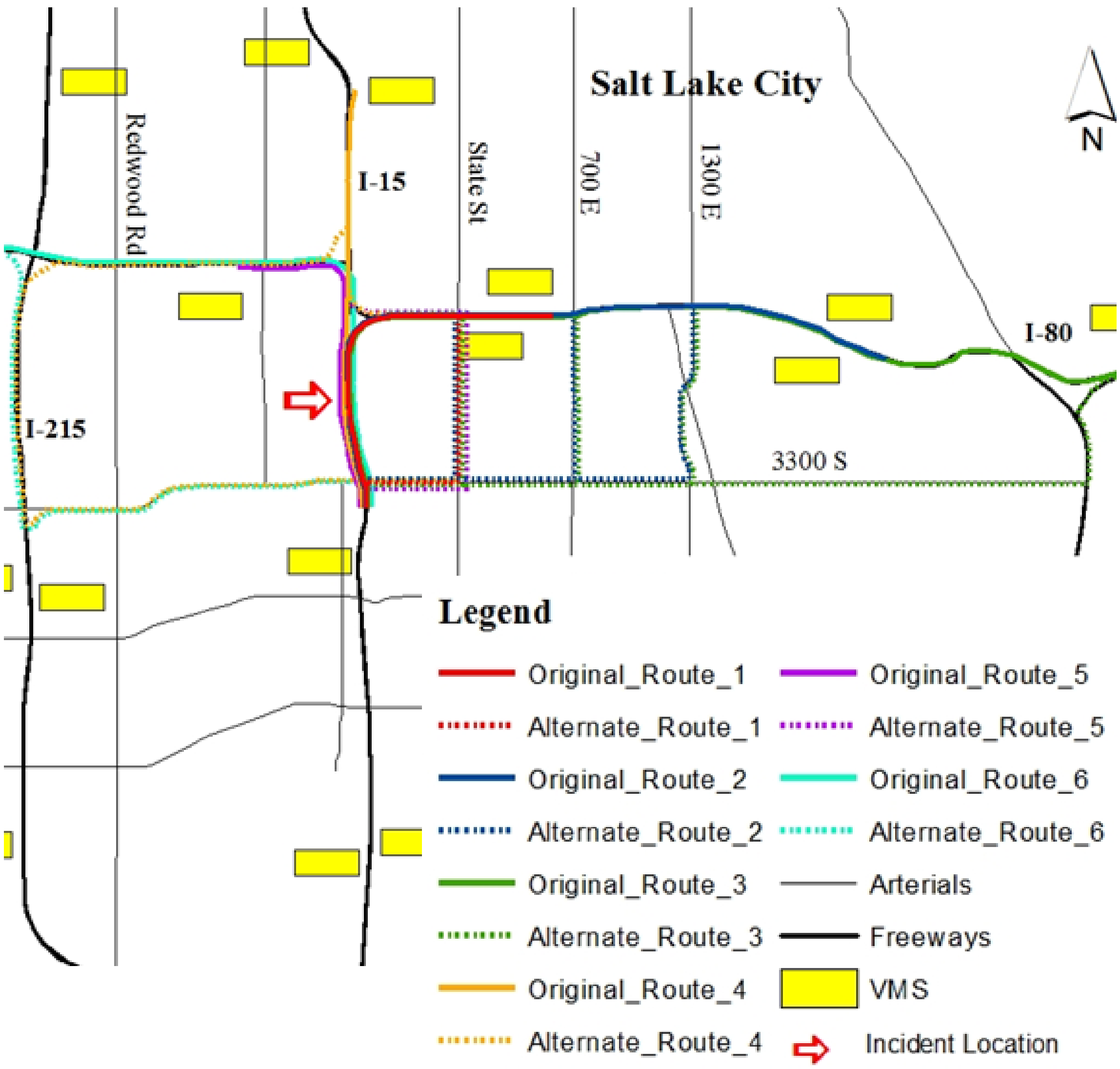


FIGURE 21 Original and Alternate Routes for Incident Location 2

Table 21 Diversion Rates in % for Incident Location 2

Original Route	Partial Route	VMS Level 0	VMS Level 1	VMS Level 2	VMS Level 3
1	1	0	94	88	20
	2	0	6	12	80
2	1	0	91	84	44
	2	0	3	4	15
	3	0	3	5	24
	4	0	3	7	17
3	1	0	93	90	55
	2	0	7	10	45
4	1	0	94	74	40
	2	0	3	12	36
	3	0	3	14	24
5	1	0	92	70	36
	2	0	8	30	64
6	1	0	94	76	44
	2	0	6	24	56

APPENDIX B

COMPLETE VISSIM OUTPUTS FOR

THE SECOND SIMULATIONS SET

Table 22 Aggregate Freeway Delay in Hours for Incident Location 2

Incident duration		30 min			60 min			90 min		
Lane Closure (%)	VMS level	Response time (min)			Response time (min)			Response time (min)		
		5	10	15	5	10	15	5	10	15
16.7	0	275	275	275	1102	1102	1102	1751	1751	1751
	1	118	130	169	836	852	917	1489	1495	1586
	2	97	110	146	684	718	706	1276	1282	1411
	3	6	149	58	9	9	53	5	4	8
33.3	0	434	434	434	1269	1269	1269	2105	2105	2105
	1	274	310	304	1139	1168	1230	1836	1963	1884
	2	138	160	215	862	909	947	1542	1582	1667
	3	35	157	13	66	52	12	3	5	11
50	0	528	528	528	1602	1602	1602	2469	2469	2469
	1	426	398	412	1666	1459	1523	2382	2400	2319
	2	260	302	374	1309	1438	1507	2219	2264	2290
	3	7	156	202	31	101	58	4	4	55
66.7	0	1075	1075	1075	2607	2607	2607	3427	3427	3427
	1	982	1046	1057	2478	2497	2436	3324	3208	3327
	2	1308	1017	1309	2341	2454	2489	3058	3142	3315
	3	129	216	350	308	561	945	380	798	1345
83.3	0	1223	1223	1223	2532	2532	2532	3212	3212	3212
	1	1142	1113	1108	2472	2427	2468	3254	3411	3279
	2	1207	1208	1029	2332	2438	2629	3323	3320	3268
	3	190	389	398	688	867	1148	1256	1596	2012
100	0	1538	1538	1538	3474	3474	3474	4649	4649	4649
	1	1484	1487	1535	3412	3422	3437	4604	4588	4628
	2	1481	1485	1507	3345	3372	3428	4588	4573	4645
	3	694	919	950	2585	2797	2992	4182	4260	4467

Table 23 Vehicle Throughput during VMS Display Time for Incident Location 2

Incident duration		30 min			60 min			90 min		
Lane Closure (%)	VMS level	Response time (min)			Response time (min)			Response time (min)		
		5	10	15	5	10	15	5	10	15
16.7	0	4405	4405	4405	6793	6793	6793	9084	9084	9084
	1	4485	4483	4516	7129	7163	7102	9650	9675	9539
	2	4528	4505	4535	7359	7362	7413	9941	9936	9952
	3	3393	3361	3524	5103	5103	5324	6890	7164	7263
33.3	0	4275	4275	4275	6564	6564	6564	8607	8607	8607
	1	4485	4403	4410	6837	6826	6769	9229	9101	9150
	2	4528	4520	4491	7239	7154	7152	9731	9718	9646
	3	3393	3438	3412	5147	5482	5074	6743	7037	6766
50	0	4191	4191	4191	6129	6129	6129	8165	8165	8165
	1	4314	4346	4349	6334	6537	6472	8589	8586	8465
	2	4461	4427	4384	6804	6703	6451	8905	8869	8897
	3	3349	3438	3444	5224	5468	5072	7297	6909	6837
66.7	0	3486	3486	3486	4563	4563	4563	5840	5840	5840
	1	3629	3494	3521	4802	4704	4953	6129	6012	6021
	2	3632	3561	3481	5058	4975	4916	6259	6194	6288
	3	3377	3377	3441	5079	5001	5129	7549	6588	7403
83.3	0	3244	3244	3244	3989	3989	3989	4518	4518	4518
	1	3392	3379	3376	4248	4240	4202	4995	5006	4878
	2	3535	3417	3510	4627	4505	4342	5520	5377	5338
	3	3375	3374	3393	4972	5060	4893	6878	6543	6700
100	0	2603	2603	2603	2624	2624	2624	2605	2605	2605
	1	2801	2738	2736	2915	2901	2884	2992	2944	2859
	2	3021	2921	2861	3281	3217	3173	3363	3260	3259
	3	3466	3409	3267	4280	4205	3909	5019	4830	4493

Table 24 Vehicle Throughput for 2 Hours of Simulation for Incident Location 2

Incident duration		30 min			60 min			90 min		
Lane Closure (%)	VMS level	Response time (min)			Response time (min)			Response time (min)		
		5	10	15	5	10	15	5	10	15
16.7	0	10144	10144	10144	10105	10105	10105	9272	9272	9272
	1	10136	10120	10129	10106	10109	10096	9838	9863	9727
	2	10151	10138	10131	10131	10130	10132	10129	10124	10140
	3	7586	9660	9148	7112	7112	8626	7078	7352	7451
33.3	0	10135	10135	10135	9933	9933	9933	8793	8793	8793
	1	10113	10135	10121	10103	10119	10105	9415	9287	9336
	2	10129	10122	10121	10112	10099	10112	9917	9904	9832
	3	8088	9747	7470	8232	8832	7073	6929	7223	6952
50	0	10107	10107	10107	9529	9529	9529	8345	8345	8345
	1	10120	10106	10121	8938	9988	9858	8769	8766	8645
	2	10107	10101	10117	10082	10077	9394	9085	9049	9077
	3	7610	9787	9604	8079	8782	7540	7477	7089	7017
66.7	0	10091	10091	10091	7602	7602	7602	6001	6001	6001
	1	10090	10092	10089	8048	7917	8292	6290	6173	6182
	2	9279	10075	9383	8368	8159	7973	6420	6355	6449
	3	8176	7755	7904	7698	7127	7473	7710	6749	7564
83.3	0	9691	9691	9691	7784	7784	7784	4665	4665	4665
	1	9939	10025	10079	7648	7433	7974	5142	5153	5025
	2	9707	9688	10076	7860	8051	7613	5667	5524	5485
	3	7925	9294	7973	7448	7347	7549	7025	6690	6848
100	0	9531	9531	9531	6591	6591	6591	2692	2692	2692
	1	9674	9709	9521	6849	6799	6710	3079	3031	2946
	2	9697	9682	9743	7056	6976	6927	3450	3347	3346
	3	7922	9325	7544	7595	7687	7506	5106	4917	4580

Table 25 Network Wide Delay in Hours for Incident Location 2

Incident duration		30 min			60 min			90 min		
Lane Closure (%)	VMS level	Response time (min)			Response time (min)			Response time (min)		
		5	10	15	5	10	15	5	10	15
16.7	0	6693	6693	6693	7120	7120	7120	7558	7558	7558
	1	6563	6474	6604	6796	6650	6774	7018	6838	6987
	2	6347	6564	6503	6497	6666	6643	6546	6648	6694
	3	9605	8015	8590	10366	10366	9342	10406	10307	10071
33.3	0	6725	6725	6725	7386	7386	7386	7973	7973	7973
	1	6773	6568	6573	6937	6899	7056	7418	7370	7351
	2	6457	6602	6646	6749	6692	6658	6719	6840	6932
	3	9654	7895	9990	9674	9296	10412	10439	10376	10440
50	0	6878	6878	6878	8021	8021	8021	8772	8772	8772
	1	6841	6944	6679	7725	7290	7450	8128	8144	8122
	2	6731	6745	6618	6928	6997	7304	7587	7654	7574
	3	9771	7779	7977	9940	9417	10390	10134	10458	10487
66.7	0	7859	7859	7859	10893	10893	10893	11938	11938	11938
	1	7743	7769	7913	10226	10409	10215	11363	11520	11637
	2	7926	7677	8289	9577	9860	9920	10738	11003	11018
	3	9804	9825	9993	10469	10841	10795	10676	11119	11102
83.3	0	8684	8684	8684	12224	12224	12224	14360	14360	14360
	1	8394	8437	8345	11585	11678	11576	13843	13882	13914
	2	8363	8524	8234	10788	11152	11245	12748	13238	13189
	3	9991	8967	10365	11099	11398	11380	11937	12302	12328
100	0	9898	9898	9898	14608	14608	14608	17325	17325	17325
	1	9564	9847	9829	14072	14209	14309	16720	16924	16908
	2	9328	9643	9598	13355	13735	13738	15931	16197	16352
	3	10543	9816	11185	12683	12905	13286	14558	14948	15449

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